DTU Library

Energy for the future – with Risø from nuclear power to sustainable energy

Forskningscenter Risø, Roskilde

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

EDITED BY MORTEN JASTRUP

Energy for the future – with Risø from nuclear power to sustainable energy

RISØ NATIONAL LABORATORY FOR SUSTAINABLE ENERGY

Energy for the future

Energy for the future
– with Risø from nuclear power to sustainable energy

Translated from 'Energi til fremtiden – med Risø fra atomkraft til bæredygtig energi' by Oversætterhuset A/S
Translated from Danish

Published by:
Risø National Laboratory for Sustainable Energy
Technical University of Denmark 2008
P.O. Box 49
DK-4000 Roskilde
Email: infserv@risoe.dk
www.risoe.dtu.dk

ISBN : 978-87-550-3671-0
ISBN : 978-87-550-3672-7 (Internet)

Printed in Denmark 2008

Editor: Morten Jastrup/Mothership Media
Editorial assistants: Lars Dahlager, Maria Lund Jensen, Jeanette Ringkøbing Rothenborg, Michael Rothenborg
Design: Marianne Dunker-Jensen/Sans Grafisk Design
Set with Neo Sans
Printed by: Schultz Grafisk
Print run: 1,500
The publication can be downloaded at the Risø website: www.risoe.dtu.dk

Title: The title of the book is inspired by Risø's mission which, at the time of its 50th anniversary, remains uncannily close to that given to Risø when it was inaugurated in 1958. First and foremost, then as now, Risø is engaged in the development of tomorrow's energy technologies. In 1958, it was nuclear power. On the occasion of its 50th anniversary, Risø is working with a palette of sustainable energy sources.

Cover photo: The avenue of poplars that is Risø's 'main street'. Like the rest of Risø's 262-hectare site, the avenue was laid out by the landscape architect C. Th. Sørensen.

Energy for the future

– with Risø from nuclear power to sustainable energy

EDITED BY MORTEN JASTRUP

Contents

Preface

6 JUNE 2008 marked the 50th anniversary of Risø, representing a significant moment in the history of Danish research as well as contemporary history. Since it was established in 1958, Risø has played an active – and occasionally controversial – role in discussions about research and energy in Denmark. Nuclear power was the starting point, but over the past 50 years, Risø has seen a number of changes, and the original focus on nuclear power has resulted in numerous off-shoots. Some of these have enjoyed vigorous growth and continue to develop either at or outside Risø. Others have been allowed to grow for a couple of years, but have disappointed and consequently been trimmed off.

Despite this branching and occasional trimming, after 50 years, Risø is close to having come full circle and is now returning to its role as an institution charged, more than any other in Denmark, with answering one of the most important questions of our time: How can we get energy for the future? In 1958, it was all about developing nuclear power which could make Denmark less dependent on imported oil, and thereby ensure energy to fuel growth and the major changes that were taking place in how and where people lived and worked, and for expanding the welfare state. Denmark succeeded in doing this, even though nuclear power was dropped along the way, and two major oil crises put the entire energy system under considerable pressure. Throughout, Risø has contributed with everything from new technologies to wind turbines, better firing technologies for power plants and with plans that could ensure that Danes always have the heating and power they need.

During Risø's first 30 years, it was largely concerns for the security of supply that drove the research. Society needed a stable flow of megawatt hours in order to function. Risø could help with this. However, from the mid-1980s, the agenda changed. Now, having enough energy was not enough. The energy had to be sustainable. Risø also took up this challenge, focusing on the possibilities for Danish society, including Danish trade and industry.

On 1 January 2007, Risø became part of the Technical University of Denmark (DTU). Today, Risø DTU is the National Laboratory for Sustainable Energy. This offers new opportunities for Risø as a whole as well as for the individual employee. Employees now have the possibility of pursuing even more varied careers within the DTU group. And it gives Risø far more flexibility to draw on competencies elsewhere at the university and thereby strengthen its research efforts in order to pursue Danish and international strategic aims. Last, but not least, as part of the university, Risø is able to make more of a contribution to society through education.

Hand in hand with Risø's profile being focused on sustainable energy, there have been aspects of Risø's work which now, from an organisational point of view, are better suited to other parts of DTU and which have therefore been integrated into various DTU departments. Of course, it is sad saying goodbye to colleagues of many years, but the prospects for their research fields are greater elsewhere within DTU.

Risø used its 40th anniversary in 1998 as an occasion to write its history so that the publication could contribute to modern Danish history. The task was placed in the hands of four historians of science and technology, and resulted in a 560-page book "Til samfundets tarv, - Forskningscenter Risøs historie" (Meeting the needs of society - the history of Risø).

Now we are using our 50th anniversary to publish another book, this time written and edited by science journalists. This book provides an insight into Risø today, and how the Atomic Energy Commission's Research Establishment Risø, later Risø National Laboratory, has developed over the past 50 years. The bulk of the book is divided into a number of chapters which each describe one or more of Risø's areas of activity and their history on the site. These chapters are mainly based on interviews with employees at Risø. More people could have been interviewed, and even more interesting stories could have been included in the book. But even though it is hard knowing where to draw the line, it is necessary.

The book also has a historical chapter which retells Risø's history from an outsider's point of view, while also focusing on the moments when the most significant changes or events took place. These two approaches supplement each other. This sort of historical chapter will always tend to focus on times dominated by discussions and disagreements. On the other hand, the chapters about the individual fields of activity will convey the scientists' enthusiasm for the work and its results. I hope that readers will feel that, above all, the book gives a balanced description of what Risø is today, and what Risø has been for the past 50 years.

Enjoy the read!

Henrik Bindslev
Director

From nuclear power to sustainable energy

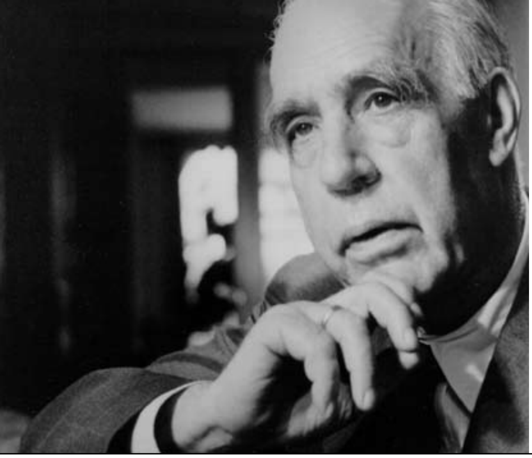
IT WAS A festive day when Research Establishment Risø was inaugurated on 6 June 1958. The royal couple was present, and the Danish Minister of Finance Viggo Kampmann and the national icon of Danish research Niels Bohr both gave speeches. Risø was inaugurated in style. And there was every reason for doing so. Risø was not only Denmark's biggest research centre to date – Risø's budget accounted for a considerable part of Danish technological research funding. It was also – and it was this that caught the attention of the media – the place that was responsible for bringing nuclear technology to Denmark. Denmark was entering a technological era, and Risø was the new bridgehead.

When it was established, Risø's ambition was to procure cheap energy to fuel industrialisation and growth in Danish society. Risø's focus is still on energy for the future – now with a requirement for sustainability.

Prior to the inaugural ceremonies, there had been about two and a half years of discussions and occasional wrestling within the Atomic Energy Commission, which was the body that managed Risø during its establishment and up until 1976. The commission was based on the Atomic Energy Committee, which the Danish Academy of Technical Sciences (ATV) had established in early 1954. The academy had looked further afield and noted the growing expectations that inexpensive nuclear energy could fuel developments towards increased industrialisation, growth and welfare. In the USA, President Eisenhower's speech to the United Nations about Atoms for Peace in December 1953, and the subsequent international work to develop civil nuclear power were probably the clearest indications of this development.

Concerns that Denmark would lag behind in the development of nuclear power – as well as noticeable concerns in society on being reliant on oil imports – prompted ATV to appoint the Atomic Energy Committee consisting of Professors Niels Bohr, J.C. Jacobsen and Thorkild Bjerge, and a fourth member, the young engineer Haldor Topsøe. The committee was to look into the possibility of using nuclear power for industrial applications. Only a few months after it was formed, the committee contacted the authorities in the USA and the UK to hear whether they would deliver uranium and reactors for a Danish test plant for nuclear energy. The responses were positive, probably not least because of Niels Bohr's international reputation, but the committee did not have the authority to sign the contracts itself. First, the Danish Government had to come on board.

The Finance Minister, Viggo Kampmann, warmed to the idea of a nuclear test plant, and in March 1955 the Government established the Atomic Energy Commission (AEK), which was made up of the four members of ATV's committee supplemented with eleven new members, largely from industry and the



Niels Bohr. The Nobel Laureate in Physics played a key role as Chairman of the Atomic Energy Commission (AEK), which was responsible for planning and building Risø. Bohr was Chairman of the AEK until his death in November 1962.

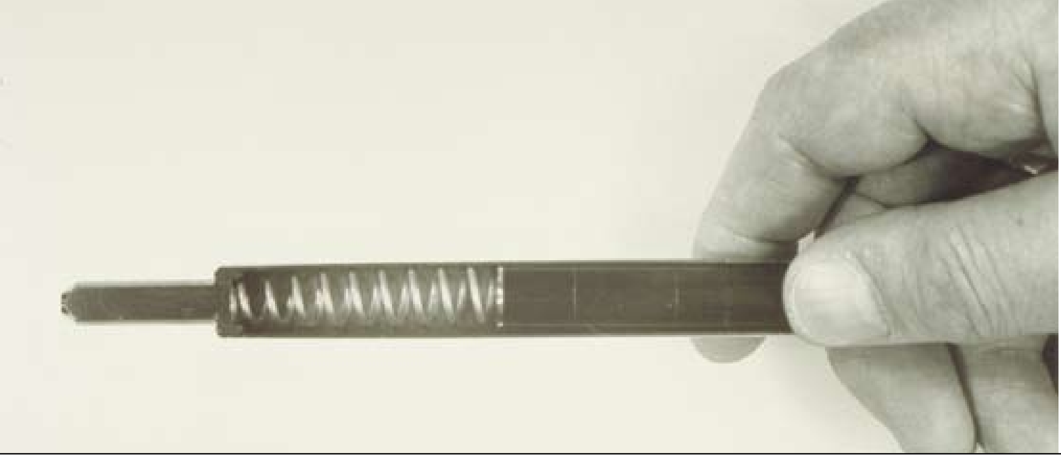
research world. As the official body, the commission could see negotiations with the Americans and the British to their conclusion, and in June 1955 partnership agreements were signed.

Building up the Danish Atomic Energy Commission and later Risø, as well as ensuring political support for the project, was largely handled in a collaboration between the commission's chairman, Niels Bohr, and the chairman of the commission's executive committee, Hans Henrik Koch, Permanent Undersecretary with the Danish Ministry of Social Affairs. Bohr and Koch had known each other since 1946, when the Nobel Laureate had contacted the departmental head. Hans Henrik Koch had earned considerable respect during the last years of the war when, as head of department, he worked to help Danish concentration camp prisoners and later had them transported home via the Swedish Bernadotte action. Bohr sought help from Koch, as he needed assistance from someone with good political contacts, and the two men established a close relationship in the following years. Koch's political contacts and Bohr's widespread reputation gave them the necessary weight to take Risø through a building phase which far exceeded the original budget, and the Atomic Energy Commission experienced its first internal quarrels about the purchase of a third reactor. There was more to come.

NUCLEAR ENERGY – WHY?

From the outset, the electricity utilities had a big representation on the Atomic Energy Commission with three out of fifteen seats. In the years that followed Risø's inauguration, disagreements within the AEK slowly developed, especially as a result of the rapidly growing budgets. The representatives from the electricity utilities became increasingly critical of Risø's work, and shortly after Niels Bohr's death the commission experienced its most serious crisis to date. It was announced publicly that no nuclear power stations would be built in Denmark in the foreseeable future. The cost was excessive compared with coal and oil-fired plants, and – which was perhaps even worse for Risø – if nuclear power became a reality in Denmark, the electricity utilities would not go to Risø. Instead, they would buy a tried-and-tested system abroad.

The Danish Technical Research Council (DTVF) followed suit and concluded that Risø would have to change its mission and management. For several years, DTVF had been in more or less open conflict with the Atomic Energy Commission about who should control Risø. It was the council's task to ensure that Danish research was forward-looking, and Risø's massive grants were a thorn in the flesh for many people, not least because it drained technically qualified staff from other institutions and businesses. However, the law did not specify whether the Atomic Energy Commission and thereby Risø fell under



Cross-section of a nuclear reactor fuel rod. This type of rod was designed to withstand temperatures of about 300° C. From 1966, Risø, together with Helsingør Shipyard and Machine Shop, tested this type of fuel rod in two reactors from abroad.

the auspices of DTVF or not. DTVF now tried to redefine Risø as a commercial research institution, but intense lobbying, especially on the part of Hans Henrik Koch, again convinced Danish MPs that an institution such as Risø was necessary, with the result that Risø continued to operate more or less as usual.

However, the conflict had far-reaching consequences. The collaboration with the electricity utilities did not improve in the following years. Risø's big prestige project – the development of a special type of reactor – had performed badly for a couple of years and was abandoned in 1964. The subsequent attempt to join a Swedish project only lasted four years before it stopped in 1968. The disagreements between Risø and the electricity utilities was also a major reason for this. At Risø, the 1963 conflict in many ways marked the start of a new way of working to which the institution has since adhered with great success. Partnerships with businesses and institutions outside Risø were extended, both in Denmark and internationally. The Government had supported Risø, but also encouraged Risø to forge stronger ties with industry. In the years after 1963, several of the departments established partnerships on both development and production, for example equipment for radiation sterilisation of medical equipment, and collaboration on the development of fuel elements with Helsingør Shipyard and Machine Shop.

Despite the initiatives, the criticism of Risø continued – that it was too large, too expensive and lacked purpose. In 1966, Risø's future was again on the political agenda, but once again it managed to rally sufficient support to enable it to continue.

YES PLEASE AND NO THANKS TO NUCLEAR POWER

The late 1960s and early 1970s were calmer. Slowly but surely, Risø extended its collaboration with the outside world, and its relationship with the electricity utilities also improved. The utilities had made it clear that they – and not AEK – decided whether and when nuclear power plants were to be built in Denmark. On the other hand, they acknowledged that they needed Risø's expertise for planning and starting up any nuclear power plants. And finally – on 17 October 1973 – it suddenly looked as though it would all become a reality. The Yom Kippur war in the Middle East resulted in the first major oil crisis. In just a few months, the oil price almost quadrupled, and the electricity utilities suddenly saw the sense of nuclear power. As did Risø, and over the next couple of years priority was again given to nuclear power, not to building its own reactor, but to providing the best possible advice on the siting, construction, operation and safety of future nuclear power stations.

The plans to introduce nuclear power were well advanced, and the first reactor was scheduled to open in 1980 – it could hardly be any sooner – but opposition to nuclear power was beginning to take

Right: The area around Risø seen from across the water. Loan bicycles are always available for getting around Risø. Far right: Risø's 123-metre-high meteorological mast. The mast was first used in 1957. Measurements from the mast are used, for example, to assess Risø's risk preparedness and in the work of the meteorologists, such as calculating the potential for wind energy and the load on the Great Belt Bridge.

shape, and in the debate that followed, Risø was destined to play a key role. Several employees were prolific writers who defended nuclear power and, in a large number of articles, identified errors and failings in the opponents' arguments. This caused certain media to accuse Risø of using propaganda to promote nuclear power and of trying to strangle the public debate. In 1976, the Danish Parliament voted to postpone a decision about nuclear power in Denmark. That year also saw big changes taking place at Risø. In the summer of 1975, Hans Henrik Koch had retired after 20 years as chairman of the steering committee of AEK. The man who replaced him, Head of Department Erik Ib Schmidt, asked the Risø employees to tone down their role in the nuclear debate, and the scene was set for changes.

In the nuclear power debate, Risø had lost considerable goodwill in many parts of the media. A critical report from the Auditor of Public Accounts, claiming that the work at Risø had drifted away from its original aim without revising the structure accordingly, did not improve the situation. The nuclear power debate also resulted in a desire among politicians in the Danish Parliament for an energy-political review of Risø's structure. People were nervous about whether members of the Atomic Energy Commission were looking after their own interests instead of those of society. The result was the Act on Energy Political Measures in 1976, which saw the AEK being dissolved. Instead, a new Board of Governors was appointed at Risø, with Erik Ib Schmidt as its first chairman. At the same time, Risø's field of work was expanded. Now, Risø was to start looking at energy in general and not just at nuclear power.

A NEW PROJECT

The late 1970s and the first half of the 1980s were characterised by careful reorganisation. The Danish economy was generally weak, and this was reflected in the grants paid to Risø. At the same time, the institution needed to strike a balance between its work with nuclear power and its research into other energy technologies and energy-related subjects. It was during this period that Risø laid the foundations for its hugely successful work with wind energy. In 1981, it became slightly easier for the Board of Governors to scale down nuclear power because, for the first time, Energy Plan 81 took a longer-term view of energy policy. It was easy to see that it was unlikely that nuclear power would be introduced in Denmark in the 1980s. By 1985, the party was over for nuclear power in Denmark when Parliament finally voted No to nuclear power stations. At that time, more than 10 per cent of Risø's employees worked with the reactors and radioactivity, but most were engaged in running the reactors or assisting the authorities, and in providing emergency preparedness services in the event of accidents at nuclear power stations abroad. Only 25 man-years – about 3 per cent of the employees – were involved in developing nuclear power per se.

From 1981 and onwards in particular, new research areas were proving interesting at Risø, but following the Danish Parliament's decision, the institution was relieved of its duty to prepare Denmark for nuclear power. The following year, Risø's name was changed from Forsøgsanlæg Risø to Forskningscenter Risø (Risø National Laboratory). Risø's task was now defined as carrying out scientific and technological research, with energy still being the principal field of activity.

The years that followed proved difficult in many ways for Risø. A growing political desire to see some tangible research results – preferably something that could be sold – paved the way for introducing new ways of managing the research. Performance contracts, evaluations and increased competition for research funding were some of the tools employed to streamline Danish research activities. As part of a major reorganisation of the Danish research establishment, Risø was now defined as a government research institution under the Danish Ministry of Energy. However, the new profile constricted Risø's departmental structure with its focus on basic research, which was not necessarily suited to taking on the role of supplier of research and consultancy within Risø's defined subject fields of energy and the environment. In 1990, a major reorganisation of Risø took place. Old departments were closed down while new were established. Materials research was defined as the third main field of activity, and it was made clear that basic research would certainly be carried out at Risø but, like everything else on the site, it had to be targeted at applications.

The same year, a number of events took place around the world that would be of considerable significance for the institution's future work. Throughout the 1980s, there was a growing awareness that pollution generated by Man's activities was damaging not only the immediate environment, but also the

Risø before building commenced. The farm Risøgård can be seen in the centre of the picture, and behind it the peninsula in Roskilde Fjord where the large nuclear reactors were constructed.

entire planet. Holes in the ozone layer above Antarctica and growing awareness of the effect of greenhouse gases from energy production and farming were beginning to put the health of the planet on the political agenda. In 1987, the UN published the so-called Brundtland Report, Our Common Future. The report highlighted the need for sustainable development and for combating pollution. In 1992, the report was followed up by the first climate conference in Rio de Janeiro, Brazil. Today, many Risø employees see these events as being of decisive importance for the institution. Greatly assisted by different Danish Governments which very early on started to focus on the climate discussion, Risø acquired a new and unifying project: Energy research for a time when fossil fuels will be phased out. Throughout the 1990s and early 2000s, research into energy technologies and methods for analysing, planning and handling energy systems became an increasingly important aspect of Risø's work. Research into wind energy and collaboration with industry in this field are probably the most obvious examples of this development.

ENTERING THE UNIVERSITY WORLD

In 2005, work commenced that has become very important for Risø's recent development. In April of that year, the Government appointed the Danish Globalisation Council. The Prime Minister himself was chairman, and the council's task was to draw up a strategy for how Denmark could become 'a leading growth, knowledge and entrepreneurial society'. The following year, the council delivered a total of 350 different initiatives. One of these was a radical reorganisation of Danish research, also called a new map of Denmark for research. National government research institutions were to be integrated with the universities, and in the negotiations that followed it was decided that Risø would be merged with the Technical University of Denmark (DTU) in Lyngby north of Copenhagen.

The decision is in line with a question which has been debated for many years – whether Risø's competencies, as a government research institution, would be of greater benefit as part of a university. Following the merger with DTU, Risø has for the first time in its history become part of the Danish university sector. However, its contact to the universities was extremely important for Risø long before the merger took place. Many PhD students and other students have done their theses at Risø, and several Risø scientists have been affiliated with the universities as professors and assistant lecturers. However, at the time of Risø's 50th anniversary, the finishing touches are being made to the first MSc study programme offered by Risø – in sustainable energy.

In 2007 – in connection with the merger with the Technical University of Denmark – a new name was chosen: Risø National Laboratory for Sustainable Energy, in short Risø DTU. At the same time,

A bird's eye view of Risø. The old reactor buildings are still standing. They have been handed over to Danish Decommissioning, which is responsible for dismantling the nuclear plants.

the activities at Risø have been tailored so they are all primarily targeted at either energy technology or planning – in addition to nuclear preparedness, radiation technology and nuclear medicine. Risø is still the place in Denmark with the greatest competencies in the effect of radio-active radiation, and how radioactive material is spread. It has maintained this function ever since its establishment.

In its anniversary year, we are starting to see yet another example of Risø's research creating jobs in industry. Topsoe Fuel Cell is in the process of preparing a production plant for SOFC fuel cells. Risø has both developed the fuel cells and trained Topsoe Fuel Cell employees in how to produce them. Throughout much of its history, Risø has enjoyed close partnerships with industrial enterprises, but the increasing political focus on research having to generate a return in the form of products which can create growth and jobs has also had a bearing on Risø. Since 2003, this work has been systematised and prioritised to a greater extent through the setting-up of Risø's Innovation Activities – RIA. On its 50th anniversary, Risø's outlook is also more international than ever. Not least, the functions that relate to the UNEP centre at Risø and Risø's contribution to the UN's climate panel (IPCC) have positioned Risø in new international partnerships that are likely to be extended in the coming years.

You can ask yourself why Risø, which was established to pave the way for nuclear power, has survived for almost 25 years after nuclear power ceased to play a role in Danish energy production. The obvious answer is that Risø has successfully managed to evolve to take on new tasks, but that is only part of the explanation.

Several sources suggest that Risø's greatest strength has been – and is – the working culture at the site. Risø is not just the sum total of all the competencies that can be found among its employees. It is very much an organisation and a way of working where the focus is on projects and on working in groups. This increases flexibility and the possibility of accommodating changing demands from the outside world. Or, as a source put it:

"Imagine if we didn't have Risø and had to build it up from scratch."

Sources: This article is based on interviews with employees at Risø, on the other chapters in this book and in particular on the book "Meeting the needs of society – the history of Risø", which was published as part of Risø's 40th anniversary celebrations.

Risø spearheads wind energy adventure

ON THE FLAT AREA of land to the south of Risø's main entrance stands a row of wind turbines. They are one of the first things visitors see when driving along the road from Roskilde, but you should not be deceived. The turbines and the test station on which they stand are no longer representative of the stage of development of wind power, even though they are still used for research. Today, trials of new wind turbine types are carried out at Risø's test facility in Høvsøre on the west Jutland coast, where turbines with a nominal capacity in excess of 4 MW have already been tested. So, wind power has not left Risø – on the contrary. However, today it is not the small metalworkers and machine manufacturers that

The wind turbines at Risø near Roskilde. These turbines are small compared to those erected today. Risø has established a test facility for wind turbines at Høvsøre on the west coast of Jutland where modern turbines generating several megawatts are tested.

Wind power was not exactly welcome when it arrived at Risø in the late 1970s, but the research institution in many ways proved itself to be an invaluable partner for the budding wind power industry. Today, Risø tries to create the basis for rolling out wind power as one of the world's leading energy sources.

construct wind turbines in a happy-go-lucky way, but a billion kroner industry with more than 20,000 employees in Denmark alone. And Risø conducts highly specialised and international-level research into what can become a central part of the switch to a fossil fuel-free society.

In just 30 years, wind energy in Denmark has grown from being nothing more than a slightly eccentric idea to one of the biggest industrial successes in recent Danish history, and one in which Risø has played a role from the outset. However, if you ask the employees how it all started, they are very matter of fact in their replies. Several people suggest that it started with a man who, despite working in Risø's reactor technology department, felt he could wear a 'Nuclear power? No thanks' badge to work.

His name was Helge Petersen. Since the 1950s, he had been employed at the department for reactor technology, but he was also an enthusiastic glider pilot who took a keen interest in aerodynamics. And when, in 1975, the alternative schooling community Tvind started to build the world's biggest wind turbine, he was one of several engineers who, on his own initiative, travelled to Ulfborg and helped design it.

OIL CRISIS LED TO AN INTEREST IN WIND

It was not as if people at Risø took a favourable view of wind in the early 1970s. Most members of the Atomic Energy Commission, which at that time was Risø's governing body, thought that Risø should concentrate on nuclear energy. However, in Danish society at large, interest was growing. In 1975 – fol-

lowing the oil crisis and a heated discussion about nuclear power – the Danish Academy of Technical Sciences (ATV) published a report on the possibilities for wind energy in Denmark. And politically, the considerations resulted in the former Danish Ministry of Trade's and the Electricity Utilities' Wind Power Programme which, among other things, set Risø's meteorology section to work, carrying out measurements on the Gedser turbine in 1977.

In 1976, the Atomic Energy Commission was disbanded, and instead a Board of Governors was appointed which wanted to expand Risø's activities. Wind energy was slowly taken on board by several departments at Risø. In 1977, Risø's management lent its support to the reactor department, where Helge Petersen worked, collaborating with the electricity utilities to build bigger wind turbines, and the materials research department was put in charge of manufacturing turbine blades from composite materials for one of the so-called Nibe turbines. These were two pilot wind turbines, paid for by the Danish Ministry of Trade and erected near the town of Nibe in northern Jutland. The blades which Risø made, partly from composite materials and partly from steel, and the experience gained from working on the Nibe turbines, helped pave the way for those blades made from composite materials which dominate the wind turbine industry today, according to Povl Brøndsted from the Materials Research Department at Risø. He was involved in manufacturing blades in what was then called the Department of Metallurgy.

"The blades were subsequently replaced, but it wasn't because of the composite materials. The problem was the steel construction in the centre of the blade, which looked as though it was about to fail. Consequently, all Danish blade manufacturers now use composite materials for everything," he says.

"NO FUTURE IN WIND"

In 1978, the Test Station for Small-scale Wind Turbines opened at Risø. This was prompted by the fact that numerous small manufacturers, smiths, electricians and others were springing up across Denmark and busily constructing small wind turbines, encouraged by favourable public subsidy schemes. Their wind turbines – often rather improvised affairs – needed to be tested and approved before they could be granted subsidies and given permission to manufacture them. This authority was given to Risø.

"To begin with, we reckoned we could approve three turbines a day, but that proved unfeasible. Often we didn't even have any drawings to refer to. The turbines were either constructed without drawings, or the manufacturers were not that keen on revealing too many of their secrets, so we had to crawl up the turbines ourselves and assess them on site," explains Flemming Rasmussen, who was the first man to be employed at the test station. He is now Head of Programme at the Wind Energy Department. Today, approving a new type of turbine involves a strictly laid-down certification process that can take up to six months. Risø continued to certify wind turbines up until about 2000, but this task is now handled by international certification bodies such as Det Norske Veritas (DNV) and Germanischer Lloyd (GL). However, Risø continues to advise certification firms.

At the beginning of 1979, the test station employed four newly qualified engineers. They had secured their own funding for a wind turbine project from a fund for unemployed academics, and they were therefore 'accomodated' at Risø, as one of them, Peter Hjuler Jensen, explains. Today, he too is Head of Programme at the Wind Energy Department.

"Risø was a place where you conducted research into nuclear power. There was a strong feeling among some people here that nothing would ever come of wind energy. On the other hand, it was also a research institution that was characterised by the curiosity you would expect in such a place, and I think people were open to and interested in what we were doing," he says. Several of the wind power enthusiasts at Risø had close links to the Organisation for Renewable Energy (OVE), and it wasn't always easy for them to explain why they wanted to work at Risø – the nuclear energy stronghold in Denmark.

MAPPING WIND RESOURCES

In 1980, Risø, in collaboration with the Danish Meteorological Institute (DMI), supplied another of the tools that has been decisive for wind energy's success – the Danish wind atlas. The atlas mapped the wind resources in Denmark, but, in addition to the maps it contained, it could also be used as a tool. The atlas initiated the development of WAsP, a calculation program which is now the world's leading method for assessing the potential for wind power. Using this calculation method, it is possible with rather high accuracy to determine how much energy a turbine will be able to produce at a given site. Based on regional wind conditions and with relatively few observations of the surrounding terrain, it is possible to assess how much energy a wind turbine will be able to generate with considerable certainty.

"We supplied the first wind atlas as a hefty scientific report, but then we had the idea of removing all the calculations and producing what we called a 'layman's model', which anyone could use. Especially in the case of small wind turbines, location is of paramount importance. In fact, you don't need to move a wind turbine very much for its performance to fluctuate by up to 50 per cent," explains Erik Lundtang Petersen, who heads the Wind Energy Department. The layman's version of the wind atlas proved a huge success. Armed with this atlas, future wind turbine owners or sales consultants from the wind turbine manufacturers could, in the space of an afternoon, calculate how much energy a particular turbine could produce at a specific site. Until then, it would have taken months, if not years, to prepare an estimate with the same degree of accuracy.

In the early 1980s, the Danish wind turbine industry grew steadily, but when 'the American gold rush' happened in 1982-83, it really took off. New subsidy schemes made it extremely lucrative to erect wind turbines in the USA. So lucrative in fact that countless wind turbines were erected which either didn't function properly or were bogus turbines without generators.

"What is interesting though is that if you look at which turbines are still running today, it is the Danish turbines," says Peter Hjuler Jensen. The huge demand from the USA saw the establishment of a number of new wind turbine manufacturers in several countries. But, like all gold rushes, it was short-lived. In 1987, the subsidy scheme was discontinued, and the global wind turbine market collapsed. The collapse hit hard, but not as much in Denmark as elsewhere. The domestic market, which by then was well established, meant that at least parts of the Danish industry survived. Many companies were re-structured, but they pulled through, so when a new market opened up in Germany in 1990, followed a few years later by Spain, the Danish wind turbine industry was the only one able to meet demand from the new customers.

SYNERGIES CREATED SUCCESS

Since then, the wind turbine industry has grown rapidly, and wind turbines today are one of the fastest-growing energy technologies. When you ask people at Risø why wind energy became so successful in Denmark, there are several explanations. Despite everything, it was not a matter of course that a company such as Vestas, which produced muck spreaders, should become the world's biggest wind turbine manufacturer, or that the furniture manufacturer Lunderskov Møbelfabrik should become LM Glasfiber, the world's leading turbine blade manufacturer. What all the explanations have in common however, is that there were a number of factors and players that worked well together.

"Risø was special in that it had the hardcore technical qualifications at the test station and the meteorologists, who had an overview of the resources, almost right from the outset. In other countries, these things were usually separate entities, which meant that the collaboration was not as intense as here," says Erik Lundtang Petersen. Regarding the development of suitable materials, it was necessary in many ways to start completely from scratch in Denmark. Senior Scientist Aage Lystrup Scheel from the Materials Research Department sees this as a key contributory factor to Denmark having a technical lead over other countries:

Risø’s wind atlas

The Danish wind atlas started as a mapping of the areas in Denmark that offered the best wind conditions for wind turbines. Originally, the work was only going to look at the best location for two test turbines, but it grew to encompass all of Denmark.

Based on the calculations which were used for the wind atlas, scientists at Risø developed WAsP (Wind Atlas Analysis and Application Program). This is, in effect, a calculation method – that then became a computer program – which can be used to determine with great precision the best site for a wind turbine. It is not enough to know the general wind conditions for an area. Woods, a range of hills, buildings and many other factors all influence how the wind blows through the wind turbine, and with what strength.

Using WAsP, it became possible, in the space of a few hours, to derive a reliable estimate of how much energy a wind turbine could generate at a given location. WAsP divides the terrain around a planned wind turbine up into fields. Data on height factors and area use in each of the fields – together with general data for wind conditions in the region – result in a picture of wind resources at the place in question. After the Danish wind atlas, Risø produced, in collaboration with a large number of EU countries, the European Wind Atlas, which was published in 1989, and several other countries have subsequently also been involved.

Today, the Wind Energy Department has produced wind atlases for numerous different countries, performed calculations for countless wind turbine projects based on the WAsP methodology and, in particular, sold WAsP calculation programs to more than 100 countries worldwide. It is by far and away the most popular tool for deciding the location of new wind turbines.
Read more at www.windatlas.dk

"When I was assigned to the task of making wind turbines from fibre composites, we in Denmark did possess some basic know-how about how to make materials which are strong and sufficiently flexible, but we had no experience at all about how to use them in practical designs. Other countries had that experience, gained from their aero or space industries. There, weight was all-important, not price. So they spent far too much energy – and above all time – trying to reduce the weight of their blades. We, on the other hand, didn't have nearly as many qualms about making something that was first and foremost practical. The blades were unbelievably heavy compared to the blades we can produce today, but they held. Our design philosophy of over-dimensioning the blades also meant that we were among the first in Europe to present a usable blade concept," he explains. Povl Brøndsted adds:

"Our approach also made it easier for us to optimise the production processes for the turbine blades. The others tried to apply what they knew about making aircraft wings from metal to making turbines from composite materials. We could start from scratch by designing blades for turbines using composite materials." Most important though was the successful interaction between research, industry and the public authorities. Knowledge, enterprise and good economic conditions created a powerhouse in which the wind turbine industry could grow and develop and overcome the various teething problems.

GREW TOGETHER

"It has been an advantage that industry and Risø 'grew up together'. We started out on a very humble

scale, as did the various turbine manufacturers. We have developed together," says Flemming Rasmussen. Peter Hjuler Jensen adds:

"There were several places that tried to do the same. The difference with us was that we administered an approvals scheme. It forced everyone manufacturing wind turbines to enter into a dialogue with us. Even though – especially in the early days – they were sometimes concerned about revealing secrets, it meant that we interacted extremely well with the industry, where we could always gather experience and challenge the industry with new knowledge."

However, the collaboration between the wind turbine industry and Risø hasn't always been plain sailing. It has always been necessary to decide where to focus efforts between very forward-looking basic research, which the industry might regard as being too nerdy, and the actual development work, which the manufacturers' own engineers could perform just as well. But the mutual benefits of the collaboration became apparent when the newly elected Liberal-Conservative Government in 2001 made drastic cut-backs in the level of funding for wind energy research. A planned expansion with 20-30 employees had to be shelved, but the industry stepped in with orders, which meant that Risø could retain its expertise with its existing employees.

"It really hurt, and for a time I really thought that there was an excess of commissions from the industry, but now the mood has changed again and we have a sensible distribution of tasks," says Erik Lundtang Petersen. Today, the major wind turbine manufacturers and their development departments have seen impressive growth, thus making it easier for Risø to concentrate on research for the future. The research funding is largely channelled through major international research programmes into completely new wind turbine types, the development of new materials and new production methods. Significant efforts are being committed to calculating wind factors, the reactions of the wind turbines, energy production and, not least, how to integrate a huge number of new wind turbines into the existing energy systems, which are based on power plants with more predictable energy sources.

Hand in hand with the wind turbine industry having grown so large, Risø's role has changed. The industry's own engineers design turbines, but Risø contributes on several fronts. Aerodynamics research results in new design programs, for turbine blades for example. Research into new materials offers the possibility of cheaper or more environmentally friendly production – sometimes both. At the Materials Research Department, staff also conduct research into superconducting materials for the generators of tomorrow. And new equipment is continually being developed which can make the turbines even better.

"For example, we are in the process of constructing an instrument which previously we could only have dreamed about. Using a laser, we measure the turbulence in the atmosphere around a wind turbine, and thereby get a much better idea of the loads to which the turbine will be exposed. This can be used to regulate the blades to ensure they are always functioning optimally," explains Erik Lundtang Petersen.

If this seems ambitious, it is because the challenges are considerable. The merger with the Technical University of Denmark in 2007 has helped to further strengthen Risø's international position within wind energy research, making it possible to now implement even bigger research projects. And they are certainly needed.

"In Europe, the plan is that 30 per cent of electricity consumption must come from wind by 2030, with about half of this coming from offshore wind turbines. There is a similar plan in America. This means that it is necessary to erect a 1.5 MW turbine every single hour from now until 2030. And the Chinese will doubtless have to erect twice as many. This requires huge efforts," says Erik Lundtang Petersen.

A fast-growing energy source

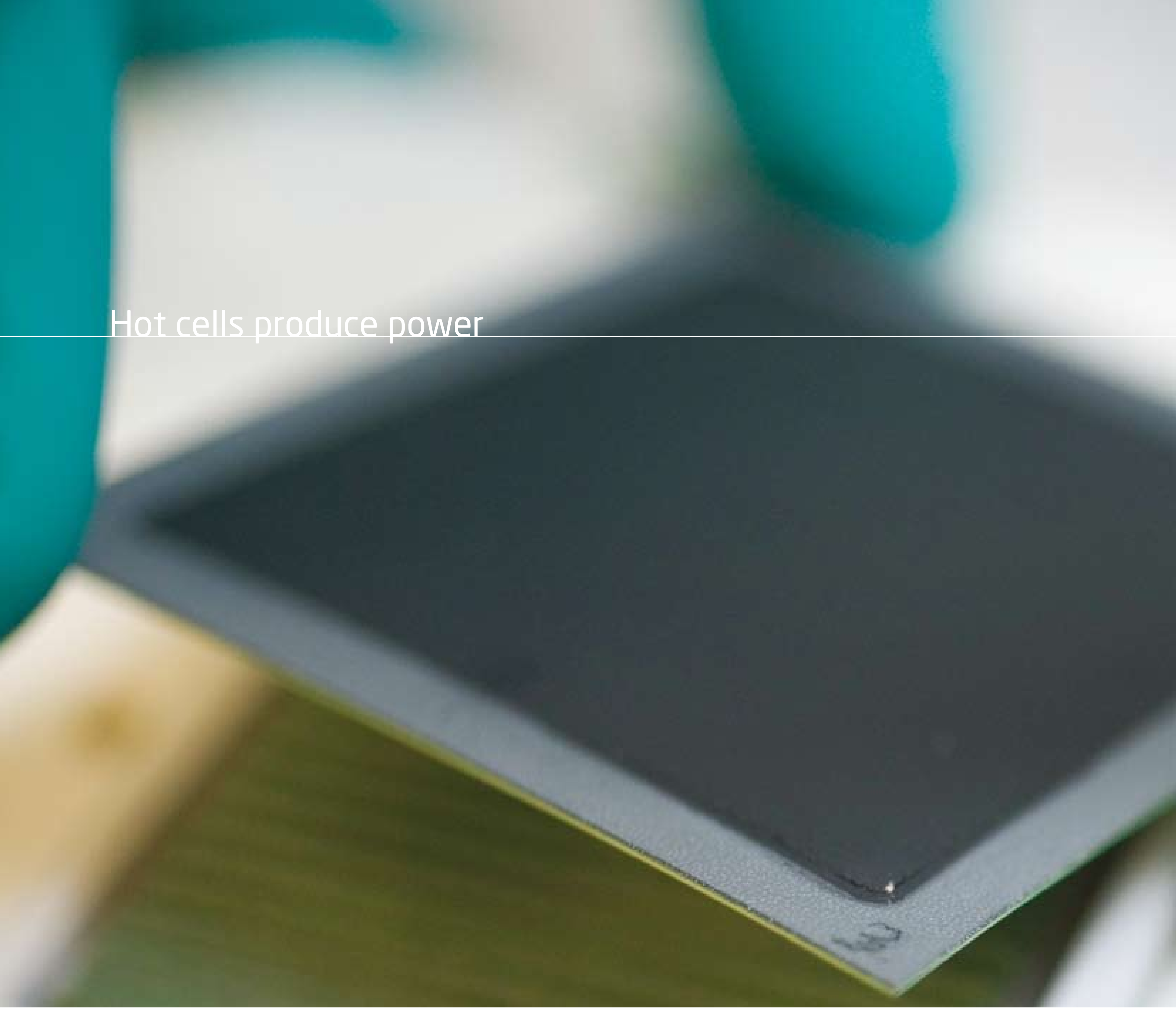
Today, about one per cent of world electricity production is generated by wind energy, while installed power is increasing by almost 30 per cent per year. This means it is doubling almost every three years.

Consequently, wind power is one of the fastest-growing energy technologies. By comparison, only solar cells are growing slightly faster, but wind energy is a far more mature technology. Today, about 50 times more energy is produced from wind than from solar cells.

Wind is therefore one of the strongest candidates for playing a key role in future energy production. Energy supplies are expected to become far more diverse than has been the case so far. In the 20th century, fossil fuels, with a bit of nuclear power and hydroelectric power, accounted for almost all world electricity production. In future, electricity and heating will come from a mix of hydroelectric power, wind energy, biofuels, solar energy, nuclear power, coal, natural gas, geothermal energy, wave energy and possibly also fusion energy. Just to mention some of the most obvious sources. In other words, we must become used to the fact that energy can come from many different sources, and we must learn to get the various energy sources to work together.

The challenge posed by wind energy is that production fluctuates according to the weather. It is therefore important to explore how energy systems can accommodate a significant share of wind energy. Various options for storing wind energy are also being considered. For example, the energy could be transformed to hydrogen, which could be used at a later date to produce electricity in calm weather. If electric cars become widespread, their batteries can also be used for storage.

Hot cells produce power



IT DOES NOT draw much attention to itself in the terrain leading down to the inlet. In fact, on the map of Risø it can be hard to find the wooden hut which, with its laconic name Building 775, is the headquarters for the Fuel Cells and Solid Chemistry Department at Risø.

And even once you step inside, there is little to suggest that the hut is the centre for world-leading research within fuel cells as well as the heart of one of the first major Danish industrial projects on the much discussed cells which are expected to revolutionise large parts of the energy sector.

However, casting a glance at Head of Department Søren Linderoth's bookshelves gives you an idea

An SOFC fuel cell, the type being developed by Risø. SOFC cells have the advantage that they are efficient and can use different types of fuels. Below: Samples of metals for storing hydrogen. Hydrogen reacts with the metal to form a new compound.

The climate, security of supply and better utilisation of renewable energy are in focus for Risø's work with fuel cells and hydrogen. As with so much other research on the site, it has its roots in nuclear research.

of the mentality that characterises the work at the department. Erudite volumes about the chemistry of solids and inch-think tomes describing the technical finesses of different types of fuel cells share the shelf space with the business guru Jack Welch's recipe for winning in the business world and several books about management and leadership.

So the scene is set. For while the starting point at Risø is research, it is not enough in itself, explains Søren Linderoth: "Our aim has never been research for its own sake. It needs to be used for the benefit of society," he says.

The history of fuel cells at Risø officially started in 1989, and is in many ways a classic Risø story. Firstly, it involves using competencies acquired within one field of research to head off in a completely new direction. Like many other things which are researched at Risø, the fuel cell scientists can trace their roots back to research in nuclear power. Secondly, it is a story about taking a targeted approach to pursuing the research areas where it is possible to make a difference. The first step towards setting up a specific department for fuel cells was a major survey to establish the areas in which Risø's efforts would be most worthwhile. Thirdly, it is a story about close collaboration with industry – in this case the company Haldor Topsøe A/S.

To say that the work with fuel cells started at Risø in 1989 is, however, not quite true. It was the year that the Materials Research Department in collaboration with the Danish Energy Authority, the electricity utilities and the companies Innovision and Haldor Topsøe initiated a major study to identify whether they should throw themselves into fuel cell research. However, the idea that Risø could play a role was based on the competencies which the national laboratory had possessed for far longer.

A fuel cell works in may ways like a battery. A material which can conduct electrically charged particles – ions – is placed between two electrodes. When fuel and air is added, the chemical reactions create a voltage difference between the electrodes, and electricity is produced. The principle is unbelievably simple, but getting it to work in practice and at a sensible price per kWh is unusually complex.

FROM REACTOR AND BATTERIES TO FUEL CELLS

At Risø however, scientists did not start from scratch. They knew a lot about transporting ions from their research into materials for nuclear power. Knowing the ability of materials to conduct both ions and heat is essential when designing fuel elements for reactors. By the end of the 1970s, scientists at Risø had realised that what had been learned about ion transport through working with nuclear materials could be applied to another research field: batteries.

"Back then, there were still several large Danish battery manufacturers with which we collaborated, so in about 1980 we started carrying out research into lithium-ion batteries," says Allan Schrøder Pedersen, Head of Programme at the Materials Research Department.

He started at Risø in 1977 in another research area that would also come to play a big role – hydrogen – and which was also based on research into nuclear power. Hydrogen is formed in reactors. The hydrogen can be absorbed by the materials in the reactor and make them fragile. Hydrogen can also be present in the non-radiated materials, for example aluminium, and Risø therefore amassed consider-

Topsoe Fuel Cell's factory under construction in autumn 2007. The factory will produce fuel cells developed at Risø. Several employees have spent time at Risø to learn the production techniques.

able know-how about how hydrogen affects various materials. From this research and encouraged by the oil crises, an idea and a new field of research arose at the research centre near Roskilde, says Allan Schrøder Pedersen. At the same time, the industrial enterprise Haldor Topsøe A/S contacted Risø for assistance in separating gases for the industrial use of hydrogen

"It was possible to isolate hydrogen by diffusing it through a membrane made from the metal palladium, and one day a colleague happened to ask himself how much hydrogen could actually be bound in such a membrane. That's how we started working on hydrogen storage," describes Allan Schrøder Pedersen.

Throughout the 1980s, interest in and grants for the new energy technologies fluctuated in step with the oil price, and with the possibility of using the research results together with Danish companies. By the end of the decade, the large Danish battery manufacturers had closed down, and the oil price was again low. Hydrogen and battery research was put on hold, but the revival of interest in global climate change and more environmentally friendly energy technologies again opened up the possibility of using the expertise.

CONCENTRATED EFFORTS

The aforementioned analysis of Risø's potential within fuel cell research had a satisfactory conclusion. The parties concluded that Risø should look into the development of a specific type of fuel cell, the so-called SOFC fuel cell, which is characterised by having a permanent non-fluid electrolyte, and which

Equipment for measuring the conductivity of materials at temperatures of up to 1,000°C. The SOFC cells which Risø works with usually function at between 600°C and 1,000°C.

Several types of fuel cell

Fuel cell is a general term for a number of different technologies which all convert fuel – often hydrogen – to electricity and heat through chemical processes on the surface of an electrolyte. The most interesting types of fuel cell are SOFC cells, with which Risø is working, and PEMFC cells. There are key differences in the way in which the two types function, and thereby their potential applications.

SOFC (Solid Oxide Fuel Cell) cells function at a high temperature, usually between 600°C and 1,000°C. The cell is efficient because the fuel (which can be natural gas, hydrogen, biogas, ammonia etc.) is efficiently converted within the cell. Moreover, the high temperature means that the heat can be used for other purposes, including the further production of electricity together with, for example, a gas turbine. Some of the challenges involve starting up the cells sufficiently quickly and ensuring that the cells can withstand being repeatedly cooled down and heated up.

PEMFC (Polymer Electrolyte Membrane Fuel Cell) cells operate at a lower temperature, usually 50-80°C, and burn either pure hydrogen or methanol. PEMFC is currently regarded as the ideal choice of fuel cell for producing electricity from hydrogen in cars. They also have a solid (although soft) electrolyte which starts quickly and delivers considerable output relative to their size. On the other hand, they are susceptible to impurities in the fuel (the hydrogen must be very pure), and it is hard to handle the amount of water which is formed on the cathode side of the cell. This type of fuel cell must use platinum as an electrode, which means that it is hard to price it attractively for the transport sector.

Source: Risø Energy Report 2007

operates at very high temperatures. The analysis showed that SOFC cells had the potential to become a truly successful technology – the high temperature made them efficient, made it possible for a variety of different fuels to be used and, as a research area, they were considered virgin territory.

"In other words, we could see that this was a place where Denmark could contribute, and it could even become something really big," says Søren Linderoth.

At Risø, SOFC fuel cell research started in 1990. Five years later, the scientists at Risø had built their first stack – a collection of fuel cells that function together to produce electricity – in addition to all the work of finding materials that could withstand the 1,000-degree-hot cells, designing testing methods etc. From 1995 to 1998, scientists worked on the so-called second-generation cell. To cut the cost of a stack, it was necessary to replace the ceramic sheets between the individual fuel cells with metal sheets. However, before this could happen, the operating temperature had to be reduced to below 800°C without compromising efficiency. In 1999, Risø could present its first second-generation stack. At which point industry really started taking an interest.

SECOND-GENERATION STACK PULLS IN THE FUNDING

Throughout the 1990s, there were periods when it was difficult to attract a steady flow of funding for the field, and several times the project was threatened with closure, but when a second-generation stack was ready, Haldor Topsøe A/S increased its support. Backed by money from the company, the 25 or so employees in Risø's research programme for fuel cells could markedly expand their activities. By 2006, it had become such a big field of research that, together with solid state chemistry, it was given its own department with a total of 60 employees, a number which, at the time of Risø's 50th anniversary, has grown to 120.

At the same time, scientists are now working on the third generation of SOFC cells, and Haldor Topsøe A/S has started the subsidiary Topsoe Fuel Cell A/S, which is in the process of establishing the first Danish industrial-scale production plant for SOFC cells. The idea is to construct small plants which, for example, produce electricity for trucks so they don't need to keep their engines running when stationary. On a larger scale, the same type of plant can replace the auxiliary engines which today supply electricity on ships, or the SOFC cells can be used for small domestic CHP (Combined Heat and Power) units which, unlike conventional oil-fired boilers, can supply both electricity and heating simultaneously. In recent years, core employees at Topsoe Fuel Cell have been trained in fuel cell production at Risø.

"We can pass on competencies to them in how to produce cells, while they help us, because they

Microscopic examinations of materials for SOFC fuel cells.
Right: Close-up picture of an SOFC cell.

handle some of the more routine work down here. They call it 'blue-collar' work because it is characterised by cells having to be produced," says Søren Linderoth, who is extremely satisfied with Risø's collaboration with Topsoe Fuel Cell.

"Industry has other criteria for what makes interesting work compared to those we might have prioritised. They can ask which requirements are the most important to fulfil for a technology to be introduced to the market. Is it the output? Is it the lifespan? Price? We can try to address these questions ourselves, but it is much better when industry plays an active role," says Søren Linderoth.

He also believes it is relevant that Haldor Topsøe A/S has a tradition for working closely with scientists. "Haldor Topsøe himself was Chairman of Risø's Board of Governors, and the company has always stressed the importance of research, so there is a mutual respect which is very beneficial," he says.

The collaboration with Topsoe Fuel Cell accounts for only part of the department's work. The scientists continue to look for new areas where they can use the knowledge that has been acquired. One of the fields which Søren Linderoth believes will soon produce results is partly the cleaning of flue gases and partly the development of magnetic cooling, which is a more environmentally friendly way in which to cool or produce heat pumps. In both cases, it builds on knowledge from fuel cell research etc.

OIL'S SUCCESSOR

And then there is hydrogen. Because, even though the SOFC cell is not dependent on hydrogen in order

to work, as are most types of fuel cell, hydrogen has again become an important research field at Risø. When oil, coal and gas need replacing because they exacerbate the greenhouse effect, a new material will be needed to transport energy around the world. Many people believe that hydrogen will be able to serve as this new 'energy carrier'. However, to produce hydrogen in the volumes which are being mentioned, there are two things that need to be mastered: It needs to be produced cheaply – preferably using renewable energy – and it is necessary to find an inexpensive and practical storage solution. Søren Linderoth's department is working on hydrogen production. In principle, the process that creates electricity in a fuel cell can be reversed. If you add electricity, for example from a wind turbine, and water, a fuel cell can convert water to hydrogen and oxygen.

This process is called electrolysis and, by drawing on the team's experiences from its work with fuel cells, it is another field where Risø stands a good chance of leading the way, according to Søren Linderoth.

"We have demonstrated the best results so far measured in terms of how much hydrogen we can produce per square centimetre of electrolytic cell," he says. Using these cells, Risø can also produce synthesis gas (a mix of hydrogen and carbon monoxide) from water and CO_2. With this synthesis gas, it is possible to produce methanol, for example.

"It is obviously because of the department's excellent results within electrolysis and SOFC that a large foreign company wishes to collaborate with the department on high-temperature electrolysis," says Søren Linderoth.

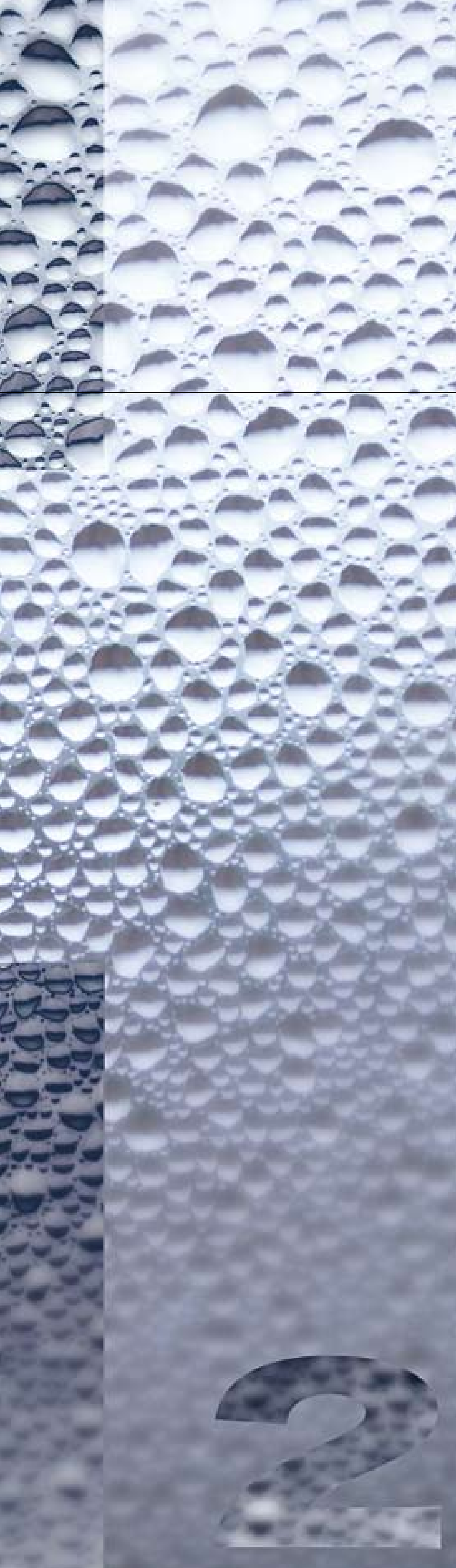
But one thing is being able to produce hydrogen. It is another to package it relatively densely – and safely – so that all sorts of people will use this explosive gas as a fuel for their cars or as a domestic energy source to fill up their oil tanks. This is Allan Schrøder Pedersen's field at the Materials Research Department. When, at the end of the 1990s, there was again considerable focus on energy technologies, the previous work with hydrogen storage was restored to favour. The work was now directed at storing hydrogen in nano-structured metals and alloys. Metals can bind hydrogen so it takes up very little space. Unfortunately it is heavy, and it can take time and energy to release the hydrogen again, but these challenges are now being addressed at Risø.

"Over the years, we have successfully switched focus several times, but we have always added to the pool of knowledge. For example, what we know about hydrogen storage comes, in fact, from knowledge about gas-metal reactions, which is vitally important for a number of significant technical processes and for many areas of the new nanoscience and nanotechnology. It is often said that it takes ten years to build up a good research group, but only ten minutes to destroy it. Which is why I believe this is the right way to work for a place like Risø," says Allan Schrøder Pedersen.

However, working at the leading edge of energy technology is also risky. In recent years, there has been a growing level of interest in new battery technologies. So much in fact, that people are starting to say that fuel cells and hydrogen will perhaps come to play a lesser role in tomorrow's energy system than was thought just a few years ago.

At the same time, the market prospects for Risø's SOFC fuel cells change almost as every month passes. But this is all part of the game when developing new technologies, says Søren Linderoth, who is not worried. Even though there is a risk of concentrating on a technology which in the long run does not turn out to be the big winner – as was the case with nuclear power in Denmark – the work is not wasted, he believes.

"A place such as Risø must dare to take the risks and follow the paths which industry is not yet prepared to tread. And as long as we are doing something that works, I am sure that, one way or another, it will be used," says Søren Linderoth.



Hydrogen society

Oil is, in many ways, a fantastic resource. It is easy to extract, there is – or has been – plenty of it, it is easy to transport, and it can be refined and processed to produce many different products. None of the new energy technologies which are on the market or being developed can compete with oil in terms of all these properties. However, by creating technologies which can each match some of oil's advantages, scientists hope to create the foundation for an oil-free world.

An important element here is that a new 'energy carrier' is developed, a medium which can store energy and, in particular, move it around. Many people see hydrogen as a potential candidate for fulfilling this role. The expression 'the hydrogen society' or 'the hydrogen economy' covers a vision of how the world can be organised with hydrogen as the primary energy carrier.

Hydrogen can be produced from water using electrical energy. And hydrogen can be used to produce electricity. In this way for example, power from wind turbines can be converted to hydrogen, which is then stored and used on days when the wind is not blowing. Or cars can fill their tanks with hydrogen instead of petrol, with a fuel cell supplying energy for electric motors.

As an energy carrier, hydrogen offers a number of advantages. It can be produced anywhere, as long as there is ample electricity. It is non-toxic, and supplies will never run short. On the other hand, it also entails a number of problems. There is considerable energy loss when converting electricity to hydrogen and back to electricity again. Hydrogen is hard to transport, and it will take considerable resources to realise a hydrogen society.

As a concept, the hydrogen society also faces competition. Many believe that methanol, for example, would be more suitable as an energy carrier. Or batteries perhaps.

Fuel rods paved the way for biology

THE STORY OF BIOENERGY and biomaterials is a classic example of how technological expertise in one area can bear fruit in other unexpected contexts. At least, Risø hardly envisaged being able to make bioethanol from straw or sea lettuce when, in the late 1970s, scientists tried to find a process whereby it was possible to extract the raw material for nuclear power – uranium – from the Kvanefjeld mountain on Greenland. The uranium in Kvanefjeld could come to play a role in securing Europe's energy supply.

The mountain near Narsaq in southern Greenland had relatively large uranium reserves. The problem was that it was found in very low concentrations. The solution was to drop the pulverised material from the mountain into water, add oxygen and subject it to massive pressure and heat in a tubular react-

Straw and other plant materials, which have previously been regarded as residual or waste products, are being explored as a potential resource, thanks in part to research at Risø.

Strong materials were required to encapsulate the massive forces of nuclear power and, using Risø's knowledge about fibre-reinforced metals for reactors, research has been conducted into biological fibre materials, which today has led to the development of wind turbine blades and a biological chair made of densely woven flax and biopolymers. Risø's research into tomorrow's biofuels also has its origins in nuclear power technologies.

or, which works like an advanced pressure cooker. The process, called wet oxidation, worked. It could liberate the uranium from the ore. However, Risø's subsequent experiments showed that the process could also be used for something completely different – removing unwanted materials, such as the toxic compound phenol which stems from solvents, from contaminated industrial soil. A Canadian company took an interest in the process, which was immediately applicable. Risø therefore sold the patent to decontaminate soil by means of wet oxidation to the Canadian company. However, Risø identified further areas where wet oxidation could be used.

"In the 1990s, my input involved trying to use the process to convert straw into bioethanol, i.e. alcohol. Back then, it wasn't an idea which the research world regarded as being terribly interesting. Many people thought that it was slightly laughable and peculiar, and reacted with questions such as: What's it going to be used for, and will it pay off?" remembers Senior Scientist Anne Belinda Thomsen at the Biosystems Department.

SECOND-GENERATION IS BEST

Straw, sawdust, sugar cane bagasse and other plant materials mostly consist of sugars, although not the types that consumers normally think of as sugars: Primarily complex carbohydrates such as starch and cellulose, held together by a compound called lignin, which acts as cement. The challenge lay in 'opening' the biomass as the chemical engineers call it, so the sugar molecules in, for example, straw become accessible. If the sugar molecules are in an accessible form, it is easy to convert them to alcohol. Wet

Plant fibres being processed into composite materials.

oxidation proved to be an efficient way of breaking down plant residue into its constituent parts, which could then be attacked by enzymes and fermented to produce biofuel. Together with DTU's Professor Birgitte Ahring, Anne Belinda Thomsen found ways of improving the efficiency of the process, and by the turn of the millennium interest in this research area was quickly gathering pace around the world.

This changed in early 2000 when the Americans started using corn to produce bioethanol. This is called a first-generation biofuel, and the biofuel stems from edible crops. However, calculations of CO_2 emissions showed that producing biofuels from foodstuffs only saved the atmosphere 18 per cent CO_2 compared to petrol. On the other hand, it is possible to save considerably more CO_2 by using second-generation biofuels produced from waste products. Risø had already started researching this area in the early 1990s. In 2008, Risø is working with prototypes of a so-called bio refinery, which makes producing biofuels far cheaper and more environmentally friendly. In laboratory trials, the refinery uses the rape plant not just to manufacture diesel oil from the rapeseed oil, but also bioethanol, biohydrogen, biogas, feed cakes for livestock and plant compounds which can be used for cancer treatments. Risø also has a patent on creating biopetrol from household waste, sludge from waste-water production and nutrition-rich waste water.

SUSTAINABILITY

However, producing biofuels can give rise to serious ethical dilemmas if foodstuffs are used or fields where foods could have been grown.

"There will be serious food shortages as the world population continues to grow. Worldwide, we are now using a third of the corn grown for energy production, so it is becoming critical," says Anne Belinda Thomsen. Risø's work is based on the idea that biofuels should be produced from plant waste, and that producing bioenergy should preferably follow organic farming principles. One of the department's projects is called Bioconcens, and its purpose is to develop organic farming that produces both foods and energy, including heat, electricity and even fuels for agricultural machinery.

Current research into the future of biofuels points in different directions; in some places efforts are focusing on manipulating the plants' genetic material so that, for example, they have a very high content of oil or sugar for energy production. But the question is whether nature doesn't have a couple of aces up her sleeve. Consider algae, for example, which is a new and growing area of research because algae are rich in energy, grow quickly (just look at a river at the height of summer) and do not take up agricultural land. Here sea lettuce comes into the picture, a macro algae which, as the name suggests, resembles a green lettuce and which forms leaves several metres in size. The idea of using sea lettuce as a basis for biofuel came from the Danish National Environmental Research Institute, which has studied the algae and discovered that it boasts an enormous rate of growth: If you start with one square centimetre of algae, after 26 days it will have grown to one square metre! Moreover, sea lettuce contains equally large amounts of carbohydrates as wheat and corn.

Scientists at Risø are now studying the algae's usefulness as a raw material for producing bioethanol and biogas. DONG is also involved, because sea lettuce grows especially well if given a good dose of CO_2. Thus, if you could use CO_2 from the coal-fired power stations to cultivate sea lettuce, you would be able to produce the almost perfect fuel: A type of petrol which is almost CO_2-neutral, and which can also help the power stations to use large shares of their CO_2 emissions.

FROM STEEL TO HEMP

Risø's research into the physical materials required to build reactors and the plants that housed them also encompassed research into types of aluminium that possessed good heat properties, high strength and long durability. The research also looked at whether it was possible to use different fibres, for example glass fibres, to reinforce the metals. The research and the resulting know-how proved extremely useful for Risø with the onset of the energy crisis in the 1970s, which coincided with Danes and Danish politicians becoming increasingly opposed to nuclear power. Wind turbines now became a core area of activity for Risø, and for the Materials Research Department the challenge was clear: To create materials for wind turbine blades that were light and which could withstand being twisted, pulled and compressed under all wind conditions throughout their 20-year lifespan. This was no small task, as analyses showed that a wind turbine blade is subjected to up to 200 million bends in the course of its lifetime.

The immediate idea was to make the blades out of polyester combined with strong glass fibre, a composite material that could far better withstand the distortions. The properties of various combinations of plastic and fibre were tested in Risø's mechanical testing machines, which can compress and stretch a material up to a million times in 24 hours. The findings and data from Risø's studies were used by the budding wind turbine industry, with Vestas and LM Glasfiber leading the way by developing their first wind turbines. Both Vestas and LM Glasfiber are now giants within the wind energy sector, but Risø still has a contract with them to test their material constructions.

In the early 1990s, Risø, together with the Technical University of Denmark and the Royal Veterinary and Agricultural University, started a research programme to study the use of cellulose fibres – plant fibres – held together by plastic.

"Society was becoming increasingly interested in things being manufactured in an environmentally

friendly way, and neither carbon fibre nor glass fibre could be described as being particularly sustainable," says Research Specialist Hans Lilholt. For example, the strong carbon fibres are made from acrylic, which in turn is produced from oil. Today, the focus has largely switched to new materials, not least because they offer the most exciting challenges. However, new materials is putting it a bit strongly. Rather, they are old, strong materials in new compositions such as hemp (which we know about from the hemp ropes on sailing ships), flax fibres (from flax sacks) and jute (the plant material which is used to make hessian). The fibres usually come in bundles which are gathered and compressed in a mould together with polymers or, even better, with environmentally friendly biopolymers. Scientists at the Materials Research

In future, natural materials can form the backbone of many of the products we today make from fossil fuels. This can be as biofuel in cars or composite materials in, for example, furniture. Right: Hemp fibres, one of the fibre materials being studied at Risø.

Department are working to make the materials stronger, stiffer and less prone to one of the key weaknesses of plant fibres compared to carbon and glass fibre: damp.

"We are looking at cellulose fibres, because they are strong and light, and not because they are green, even though this is an added bonus in this context. It broadens the spectrum of materials which are available for a given application," says Hans Lilholt. The scientists at the Materials Research Department and the Biosystems Department also look at how residual products can be used to make biomaterials. The aim is that, instead of just deriving energy from the biomass, it should also be possible to get biofibres for making everyday items. As an example, Risø's spin-off company Biobiq A/S has, on a trial basis, produced three different chairs, among others Arne Jacobsen's 'Number Seven', based on jute fibres in a matrix of PLA biopolymers. It is all about trying to ensure that nothing from the biomass goes to waste. And Risø also has an activity where the remnants from bioethanol production – hemicellulose – are used to produce cling film for packaging food products.

ECOSYSTEMS AND CLIMATE

One of Risø's biomass projects differs considerably from the others: Measuring how much CO_2 is absorbed by Danish woodlands in step with increasing climate change. This can help to answer a serious question: How do ecosystems react to increases in temperature and CO_2 levels? Will the woods grow vigorously, because CO_2 is a necessary food for plants? Or will the heat cause other processes to have the opposite effect, for example by increasing the release of carbon from the soil? The measurements are called flux measurements, and the equipment is mounted on Risø's 57-metre-high meteorological tower at Sorø, where, ten times per second, it measures how much CO_2 is being transported up and down across the woods. With time, this will form a picture of whether the woods absorb or give off CO_2. Past studies show that woods give off CO_2 during the winter and absorb the same amount during the summer – on average. However, it has been shown that Lille Bøgeskov at Sorø has absorbed more CO_2 than it has given off since measurements commenced twelve years ago, when Risø pioneered such measurements. The same picture is seen in other European countries, and suggests that the woods are counteracting some of the effects of mankind's emissions of greenhouse gases. But only some of the effects, because the CO_2 content in the atmosphere is increasing year by year.

"And there is a risk that the balance changes so the woods begin to give off more than they absorb," warns Kim Pilegaard, Head of the Biosystems Department. The flux measurements at Sorø are part of a large EU project, Euroflux, with 60 partners, which in turn forms a part of Fluxnet, which is financed by NASA in the USA. At the end of the day, data from Sorø will help to create models of the world's CO_2 balance and thereby provide insight into the world's climate changes. According to Kim Pilegaard, Risø's forte in this research is that it has accumulated knowledge about a number of factors which are significant for the overall picture.

"What is unique is that we have expertise that stretches from plant physiology – how much carbon can be bound in the ecosystem – to research into the effects of climate change, opening the biomass, bioethanol production, and assessing sustainability," says Kim Pilegaard.

"The entire chain is important, and we are mastering the lot."

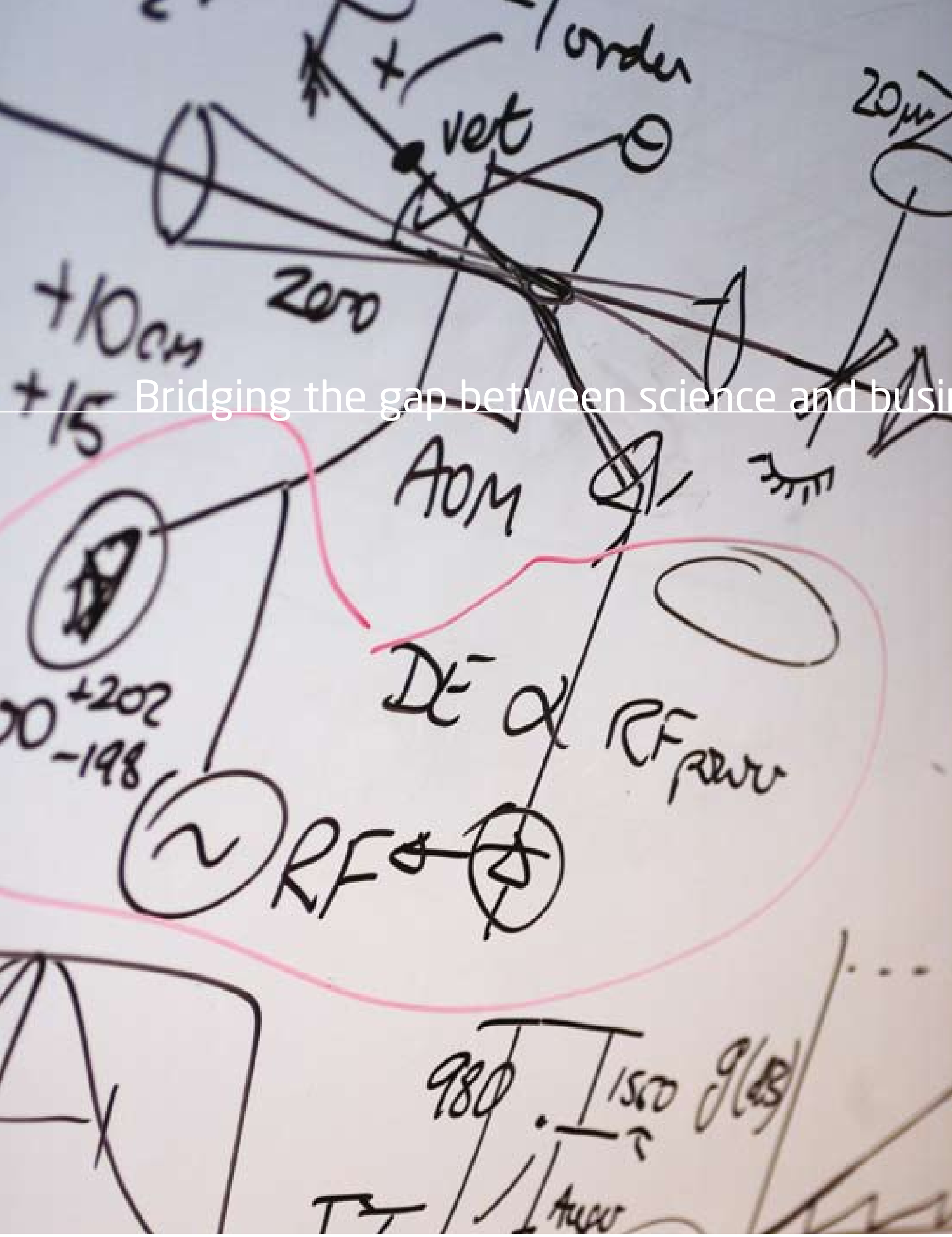
The big biofuel dilemma

An era with cheap and ample supplies of energy is coming to an end. Since the last century, we have used fossil fuels – which are in reality condensed plant remains – to run our industries and food production. However, within only a few decades, we can expect, according to various energy experts, supplies of cheap oil to dry up, if it hasn't happened already. Several energy analysts reckon that oil will have tripled in price by 2020, which changes the entire basis for the world economy.

Biofuels are therefore one of the key solutions which the world has decided to explore. These are fuels which are based on crops or agricultural residue, and which are in theory CO_2-neutral. It is undoubtedly here that most resources for alternative energy research are targeted, and especially in the form of farm subsidies.

However, first-generation biofuels, i.e. biofuels based on, for example, corn and palm oil, are being accused of being problematic because they are competing with food production. Moreover, according to some scientists, from the point of view of CO_2, there are only marginal advantages to be gained compared to oil. This is because it either takes a lot of energy to produce biofuel or because it will indirectly be responsible for large-scale deforestation.

Scientists at Risø have been aware of this for years, for which reason the research focuses on using the biomass in an as environmentally friendly way as possible, where all parts of the raw materials are used for many different purposes. Risø is therefore counting on second-generation bioenergy which does not compete with food production, for example by using straw for bioethanol, and biogas and biomaterials for producing physical products, where the production is largely organic and has what is termed sensible CO_2 accounts.



Bridging the gap between science and business

RIA – RISØ'S INNOVATION ACTIVITIES – is based in an office in the laboratory corridor in Building 108 at Risø. None of the six employees are scientists or trained lab staff. Most of them have a commercial background, and as part of the administration they might be expected to sit in the main building, 'the master bunker', or however else you describe Building 101 which houses Risø's management and administration. However, in the laboratory corridor, the innovation team has access to something that the main building is unable to offer. They can bump into the scientists on an informal basis and without any obligation, and chat on the spur of the moment about what is happening.

It started with a Roskilde Festival that caused resonances in the research world, but it was based on old traditions at Risø. In recent years, the lifelong collaboration between Danish industrial enterprises and Risø has been supplemented with targeted innovation activities.

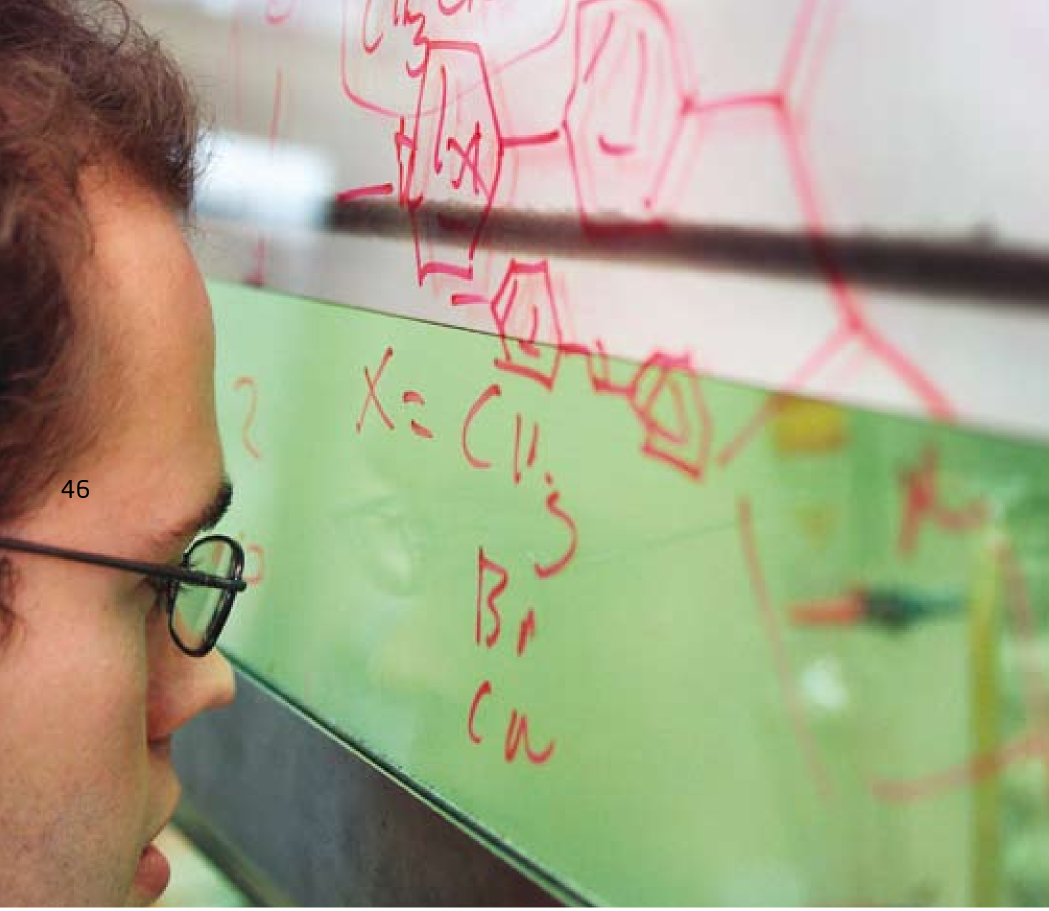
"We need to be where the scientists are. A lot of the knowledge built up over the years is lodged in their heads like goods on shelves. Our job is to bring this knowledge into play," says RIA's manager Helle Bunkenborg. RIA has several tools for this purpose at its disposal from partnerships in knowledge networks to specific workshops between scientists, businesspeople, designers, project makers or anyone who expects to benefit from inspiring one another.

"We see ourselves as matchmakers whose job is to ensure the shortest possible path from science to business," says Helle Bunkenborg.

"Risø has always collaborated closely with industry. Research has always been conducted for a purpose. However, in 2003 Risø's Board of Governors decided to work more systematically with innovation and intensify collaboration across Risø so that all competencies were involved in the innovation process," she explains. At about the same time, Musicon Valley – a growth environment around Roskilde Festival – got in touch and asked whether Risø was interested in participating in the festival.

"Some people grumbled about whether it was something we should be part of, but the idea appealed to many others, and in the course of just three weeks we knocked something together, and the result was surprisingly satisfactory," recalls Helle Bunkenborg.

The collaboration between the festival and the national laboratory had a resonating effect. Firstly, the collaboration with Musicon Valley has developed, so that several other players from the Roskilde area are now involved. Secondly, it has led to several interesting ideas, for example better windshields for microphones, wireless signal transfer from the stage to the loudspeakers, and several products within



lighting, especially energy-saving diode lights. It is hard to say how many of the ideas will actually be realised, but it shows that positive meetings can take place, especially in unexpected places. Thirdly – and no less importantly – the collaboration between Risø and Roskilde Festival was noticed and praised in an editorial in the prestigious journal Nature under the title 'Science rocks'.

"It meant that within Risø there was considerable respect for the collaboration, and the following year scientists at Risø were queuing up to get involved," says Helle Bunkenborg.

One of those who accepted the invitation from Roskilde Festival the first year was Head of Programme Povl Brøndsted. He saw it as an obvious opportunity to use his knowledge in a new context and to meet people who looked at things differently to himself and his colleagues.

"We are working with energy at Risø, and that is clearly our main task, but I think it is fine if we can spend some of our time gazing out of the window to see whether we can't spot other areas where we can use our knowledge," says Povl Brøndsted. According to him, people at Risø started thinking about innovation in a different way before 2003. He recalls crucial developments taking place in 2000, when Risø staff started looking at how the competencies gathered there could be used within the pharmaceutical and medico industries.

"A lot has happened in the past ten years. There was masses of innovation at Risø beforehand, but it has become more integrated into the system, and people are now much more aware of it," he says. In his opinion, one explanation is the increased focus on innovation in society as such and the challenges that globalisation places on Danish society.

The Danish Minister of Science, Technology and Innovation Helge Sander examines SOFC fuel cells produced at Risø's first pilot production plant.

"We have all got used to saying that we need to innovate in order to maintain our standard of living. Previously, people brought problems to us which they felt we could help solve. Now we even look at our research with innovation in mind, and we contact companies and invite them to present us with problems which Risø's scientists can perhaps solve," says Povl Brøndsted.

For Helle Bunkenborg, this change of attitude combined with greater management focus has created the possibility of taking Risø's knowledge to a broader audience – for the benefit of Risø and society at large.

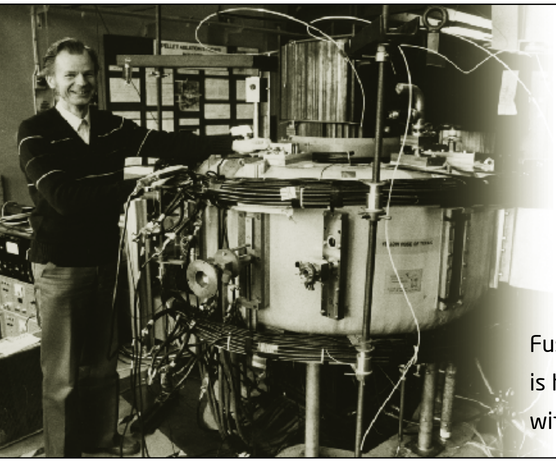
"Society is investing huge sums in Risø. The innovation activities are another way of giving something back. Denmark cannot compete on education and competencies alone. They are churning out scientists and engineers in China and India. But we can innovate. Perhaps it has something to do with the relatively low social barriers in Denmark. In any case, we can set up very informal and relaxed meetings between scientists and other groups, which is conducive to brainstorming and generating ideas," she explains. However, she makes it clear that it does not just happen of its own accord.

"RIA is a commercial bridge-builder in a scientific and technical institution. Quite consciously, we are placed among the scientists, because we need to know them, establish a sense of trust and know what they are engaged in. This is how we can best help apply their knowledge," she says in conclusion.

Harnessing natural forces

IT'S NOT SOMETHING WE think about, but most energy types actually stem from one place: the sun. Oil, gas and coal, our primary sources of energy, stem from accumulated solar energy – plants that have grown in sunlight and, over thousands of years, lain deposited and compressed beneath the Earth's surface and which can now be pumped up using drilling equipment or extracted in mines. Bioenergy in the form of bioethanol and biodiesel for cars and trucks generally comes from plants. Energy from wind turbines comes indirectly from the sun's energy which activates the atmospheric wind systems, and energy from solar cells and solar heating installations comes, of course, from the sun. The idea of fusion energy

Maintenance work at Joint European Torus, the world's biggest pilot plant for fusion energy – called a tokamak. In the doughnut-shaped ring, plasma is heated to many million degrees, where atomic nuclei melt together, releasing huge amounts of energy.
Pictured below is Risø's own tokamak, DANTE, which was in operation from 1977 to 1986.



Fusion energy – the sun's power source – offers fantastic possibilities, but it is hard to utilise. Risø has worked with fusion for years. It is now paying off with international research efforts being intensified.

is basically different: It is not energy that comes from the sun. It is the energy that is the sun. It is an attempt to recreate the huge and intense processes that take place in the stars and which can be credited with striking the Earth every hour with more solar energy than Man uses in the course of a year.

Fusion energy works by melting – fusing – light elements to form new elements that are heavier and which lie higher up the periodic table. It is in this creative process that vast amounts of energy are released. What is interesting about fusion technology is that the fuel – two types of hydrogen – in practice never runs short. The environmental problems are insignificant. The technology is safe.

"Fusion energy is an inexhaustible energy source, and the fusion reactors can function extremely well as a so-called base load – i.e. power stations that constantly deliver the basic power requirement as coal-fired and nuclear power stations do today. The potential is simply enormous, and there are no regional limits to the raw materials," says Henrik Bindslev, Director of Risø, and who previously headed Risø's research into plasma physics and technology.

But there is a long way to go. It has proved far harder to get the solar powerhouse to work on Earth than scientists envisaged. The experimental set-ups alone are extremely complex and expensive: For example, the most ambitious fusion reactor to date, JET (Joint European Torus), in the UK has an inner so-called plasma chamber where the plasma of ionised elements has a temperature of 200 million degrees – 20 times hotter than the sun! The plasma is contained within extremely powerful magnetic fields – which in a power station will be created by superconductors.

The next large experimental reactor, ITER, will be twice as large and cost 35 billion Danish kroner to build. It is estimated that the first commercial reactor will not be ready until 2050.

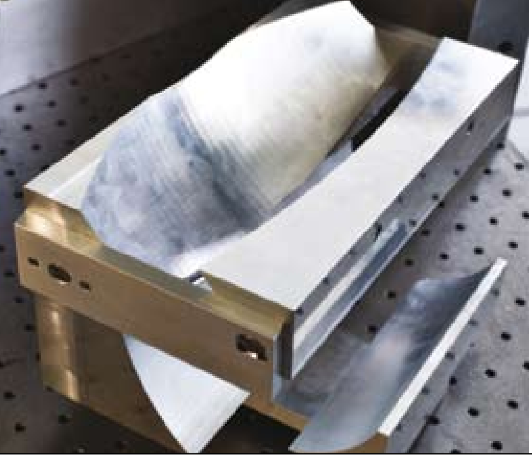
In other words, this is an extremely challenging and long-term research project involving a high degree of international collaboration, and here Risø is a small but recognised player. Risø's plasma physics and technology scientists have actually made significant contributions to several breakthroughs in understanding what happens in these highly complex fusion processes.

WORLD-CLASS DANISH RESEARCH

When research into fusion energy started in the early 1950s, it was thought that the fusion processes were relatively simple and that it would soon be possible to get a fusion reactor up and running. However, it gradually became apparent that the million-degree hot plasma in the reactor chamber behaved completely differently to what had been expected – and more unpredictably. Plasma is a term for the cloud of positive and negative particles that is formed in the reactor, and observations showed that the plasma formed almost chaotic weather systems with winds, turbulence and sudden eruptions around the edge of the plasma similar to those on the surface of the sun.

"There was no correlation between the experimental measurements being made and the models being used to predict what would happen in the fusion process," says Bindslev. It was here that Risø really started attracting international attention. Risø built its own small fusion chamber, a so-called tokamak, in the 1970s, and made several other experimental set-ups. The work gave the research institution considerable insight, among other things into how to measure factors such as temperature within the plasma. This insight meant that Risø was charged with building large parts of the advanced laser system for measuring the temperature in the JET reactor in the UK. However, in the late 1980s, international interest in fusion research – and in energy research generally – started to decline after the world had recovered from the energy crises of the previous decade.

In 2001, Risø again started taking more interest in fusion energy. Today, Risø's research into turbulence theories ranks as world-class – i.e. the fact that the plasma behaves almost as chaotically as the weather. Here, the activities were expanded again and integrated more closely with international experimental work, in particular JET. At the same time, Risø took over JET's competencies regarding the measurement of fast ions in fusion plasmas and initiated a fruitful collaboration with the Massachusetts Institute of Technology (MIT) in this field. Risø is currently leading the development and application of one of the most promising experimental methods for measuring how the high-energy ions in the fusion plasma, for example those produced as part of the fusion process, behave. Risø's Materials Research Department has also been able to supply decisive results. Among other things, the department helped to



Receiver antenna for fusion reactors developed at Risø. This is part of the measuring equipment which Risø has developed for delivery to ITER – a new large experimental reactor which will be completed by 2016.

define which materials to use in the next large experimental reactor, ITER, which is being built in France with planned completion in 2016.

However, the challenge for the test reactor, DEMO, which follows in 2033, is far bigger: A proper fusion power plant with radioactive plasma at 200 million degrees in which the reactor chamber will be constantly exposed to radiation. In fact to such an extent that every single metal atom in the DEMO fusion chamber will be physically dislodged 100 times during its lifetime. The challenge here is to find alloys that can withstand this, something which requires detailed studies of changes to the materials' inner structure and their mechanical properties. This research is being followed up by physical-mechanical models, which are used by the designers responsible for developing fusion reactors.

The research is also leading to the development of new metallic alloys and ceramic materials which can tolerate the immense loads during use. For many years, Risø has contributed to the work into studying the structure and properties of the materials, and presenting the results in models. Most recently, Risø has developed a 3D X-ray technology, called 3D X-ray diffraction or just 3DXRD, which can 'see' what takes place within a material when it is exposed to compression, traction, heat and radiation. Here, Risø is collaborating with one of the world's biggest X-ray centres, the European Synchrotron Radiation Facility in Grenoble, France. Risø has established a 3D microscope at the facility which can see what is happening within the materials' microuniverse through live video.

"It is an important new characterisation technique where we are leading the way – it was, after all, us that invented it – and which will be used to study materials that must be able to withstand being in a fusion reactor. However, when our group is challenged to study materials for fusion, we also discover and develop materials that can be used in other contexts," says Dorte Juul Jensen, who is head of Risø's Materials Research Department.

RESEARCH MEANS INSIGHT

"Can be used in other contexts." This is really true of Risø's fusion energy research. It will be a long time – probably 40 years – before the world can press the start button for the first commercial fusion reactor. For Risø though, it is as much about gaining insight into some of the most demanding technologies and some of the challenging theoretical research. A material that can withstand the forces in a fusion reactor can probably also be used to advantage in, for example, highly efficient boilers in tomorrow's coal-fired power stations or in better power lines. The research into superconductors can just as well be used for transporting power without losses from mega solar cell parks in the Sahara to Denmark.

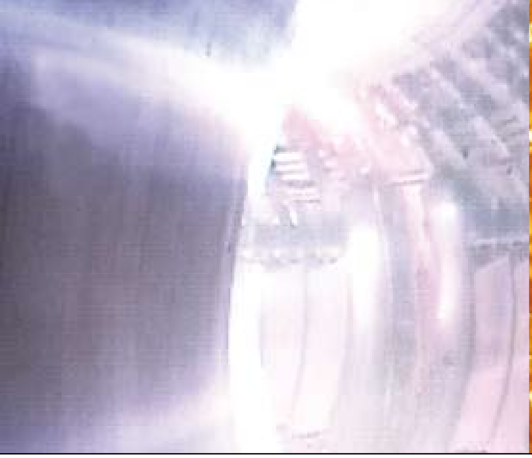
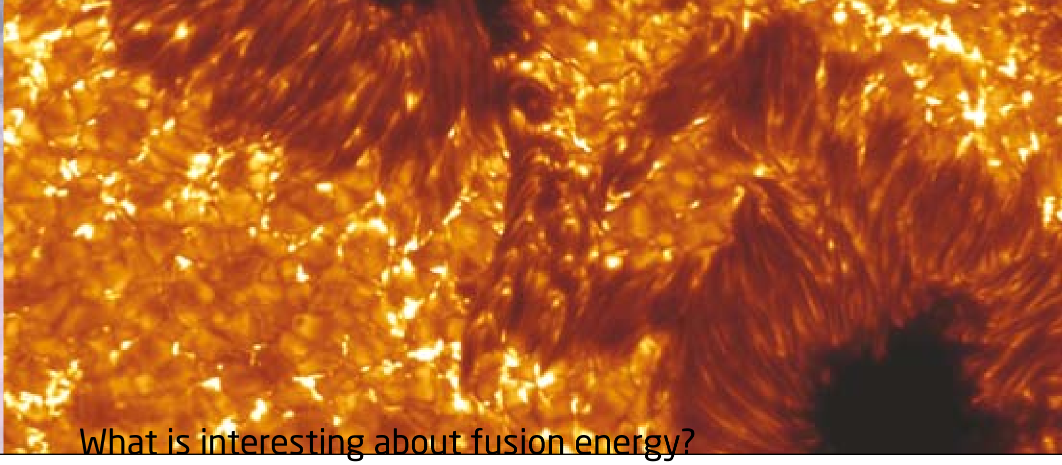
Right: The JET tokamak
(see caption on p. 49) during trials.
Far right: Close-up of the sun's surface. The sun also gets its energy from fusion processes.

"Today, we have a far more complex rationale for research, business policy and science policy than in the past. By participating in large international research projects, we gain access to a knowledge network that we would otherwise not have access to," says Henrik Bindslev.

"The same technology ends up in many places, and if we are good at high-temperature superconductors, it is good to participate in all the areas where this technology is in demand. The next large fusion reactor, ITER, involves an order for superconductors to the tune of 10 billion Danish kroner! When we participate in, for example, international fusion research, we can see which challenges are not being covered by other parties, and find out how we can match this opportunity with the competencies in Denmark," says Henrik Bindslev. At the same time, he makes it clear that politically one cannot just plan the research activities according to where the current buisness opportunities are. The long-term basic research is also necessary, so leading Danish expertise is available when the commercial opportunities suddenly arise. Research is often a lottery where you might be lucky to have just the right competencies needed to meet tomorrow's business challenges.

"With fusion research, we have bought three lottery tickets. The first lottery ticket is whether fusion energy will succeed. If it does, it will become one of the world's biggest industries, it would be terribly annoying if Denmark was not involved. The second lottery ticket is that many of the technologies necessary for fusion are already commercially relevant or will be in the very near future," says Henrik Bindslev.

"And the third lottery ticket is that if you participate in highly advanced international research, there is a good chance that you learn something."

What is interesting about fusion energy?

The need for ample supplies of cheap energy has been exploding in recent years. According to the International Energy Agency's World Energy Outlook 2007, the world will be consuming 50 per cent more energy by 2030. And what is worse is that use of the most polluting energy form, coal, is increasing the fastest. At the same time, the threat from global warming is becoming more and more pressing. It is therefore vital that we find energy types that can satisfy the world's energy needs efficiently, cheaply and in an environmentally friendly way.

For half a century, fusion energy has been the great hope for the world energy supply because it offers the same advantages as coal, oil, gas and nuclear power – large amounts of energy at all times of the day and night and independent of fluctuations in wind, sun and rainfall. Yet without polluting the immediate environment and the potentially catastrophic consequences for the climate posed by fossil fuels – and without nuclear power's inherent risks.

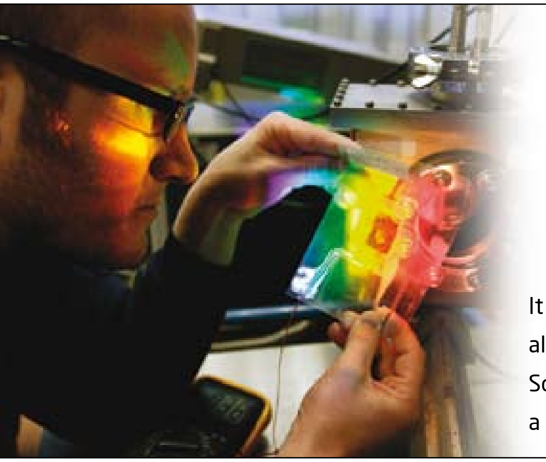
Another interesting aspect of fusion technology is that the fuel for the reactors, unlike uranium for nuclear power or coal for coal-fired power stations, will never run out. The fuel is two heavy types of hydrogen – deuterium and tritium – which are easy to produce all over the world. Deuterium is found in ordinary water, while tritium is formed from lithium, a metal found everywhere in the Earth's crust.

At the same time, the environmental problems with fusion energy are insignificant. Fusion energy gives off no CO_2 during power production, pollutes neither the air nor water and cannot, unlike nuclear power, run out of control. A decommissioned fusion power plant will certainly contain radioactive materials, but the radioactivity decays relatively quickly, and after 50 years almost all the material can actually be reused.

Polymers bring the sun to Risø

SARCASTIC COMMENTS are still heard by Senior Scientist Frederik Krebs: "I have been told so many times that the sun hardly ever shines in Denmark, and that the best way to get energy out of polymer solar cells is to burn them. But I am pretty thick-skinned. And after a while the comments are mostly made in jest, because our results speak for themselves," he says.

It was Frederik Krebs's idea to develop a completely new type of polymer solar cell which has meant that, in Risø's 50th anniversary year, there are about fifteen scientists engaged in this area. The research has also led to prizes, collaboration with industry and international partnerships – in a field which was introduced at Risø only a few years ago.



It wasn't anticipated that Risø would carry out research on solar cells – after all, the sun never shines in Denmark. But in 2000, a new concept emerged: Solar cells made from plastic – a technology that could put solar energy on a competitive footing with other energy forms.

In the late 1970s and early 1980s Danes marched against nuclear power, and the Swedish nuclear power plant Barsebäck in particular, and in favour of solar and wind energy. Many people shook their heads, including those at the research centre at Roskilde Fjord. Especially at the mention of solar power, as the sun almost never shines in Denmark. And when Risø was forced to redefine itself after the Danish Parliament's emphatic No to nuclear power in 1985, solar cells did not exactly present themselves as the new field of research, whereas wind turbines did. Risø already had several years of experience with wind turbines, the technology looked more promising and, after all, the sun never shines in windy Denmark.

There was therefore some scepticism within the institution when, in 2000, the chemist Frederik Krebs, encouraged by Klaus Bechgaard, who was head of department for physics and chemistry, wrote an application to the Danish Research Technical Council requesting funding for a Talent Project initiative about solar cells. Not that solar energy hadn't been considered before. But this was in connection with the UNEP Risø Centre supporting sustainable energy in the developing countries – not as an independent research area.

"After all, it has been quite characteristic of Risø that it is only once we have been ready to deliver outstanding, almost unique research within an area that we have started up," says Senior Scientist Peter Sommer-Larsen, Head of the Polymers for Energy Technology Programme under which research into solar cells is conducted.

"If you wanted to do research into a type of solar energy which has already been researched very extensively, the likelihood of being able to generate something of value to Danish society would be very small. This is why solar energy only made it onto the agenda when Frederik had his bright idea," Peter Sommer-Larsen explains.


The idea was to create a brand new type of polymer solar cell, combining low price and high efficiency. The idea as such is not really new: Scientists have long been looking for a way in which to kick-start the market for solar energy, a market which has not developed much since 1954 when silicon solar cells were first used to generate electricity. These were the so-called first-generation solar cells, which slowly started making their way onto Danish rooftops in the 1970s. Slowly because they were – and are – quite expensive. The second-generation solar cells were thin-film amorphous silicon solar cells, the type which is also used for garden lamps. These cells were slightly cheaper, but still disproportionately expensive relative to the volume of electricity generated. And solar energy remained a niche product.

Expectations were therefore running high that solar energy would finally emerge from the shadows cast by wind power when the first polymer cells were developed in the early 1990s. What was so revolutionary about this third generation of solar cells was their price: While one square metre of silicon solar cells costs between 1,000 and 5,000 Danish kroner, the same number of polymer solar cells could be produced for less than 10 kroner. The problem was that the energy conversion efficiency of the polymer solar cells was not particularly high, and they only lasted a few days. The silicon solar cells, on the other hand, lasted for up to 25 years. This was one of the reasons why Risø's solar cell research did not start with a number of inspirational visits to other laboratories.

"If you study other people's methods, you risk taking over their way of thinking – and making exactly the same mistakes. Of course, this does not mean that you should start from scratch, that simply involves too much double work. But if you pursue your own ideas, you stand a much better chance of making a real contribution to research," Frederik Krebs explains.

The strategy worked. In July 2005, the research team presented the patent on a brand new type of solar cell made from polymers to the Danish and international media. And the following year, Frederik Krebs was awarded the prestigious Knud Lind Larsen Prize by the Danish Academy of Technical Sciences (ATV).

POLYMER CELLS TESTED IN THE DESERT

Polymer solar cells consist of an active polymer layer sandwiched between two electrodes, a transparent electrode and a shiny aluminium electrode. The electrodes are placed on either side of the thin polymer. Production takes place in two processes. First, the transparent electrode is almost painted on in a process not unlike silk-screen printing. Then the aluminium electrode is steamed on. In the past, the cell was also encapsulated so as to protect it against oxygen and water vapours in the air, but in 2007 scientists at Risø developed a type of cell which is air-stable. Risø's solar cell team is continuously working to make the manufacturing process more efficient, but initially the primary focus was to prolong

Far left: The polymer materials in the Risø solar cells do not tolerate oxygen. So the work has to take place in sealed glove boxes.
Left: The finished solar cells.

the useful lives of the cells. They experimented with durability and thoroughly tested the most promising examples. Testing took place, for example, in the middle of the Israeli desert with the assistance of one of their international collaboration partners, the Ben-Gurion University in Negev. Or by exposing the solar cells to snow and whatever else the wind and the weather might throw at them at Risø. Or by simply leaving them under a strong lamp in one of the laboratories, round the clock, seven days a week.

After a solar cell had been left exposed like this for almost 18 months and was still working, the scientists concluded that it would probably last between five and ten years under natural conditions with nights and cloudy weather. In other words, the scientists had progressed considerably from the time when the cells lasted only a few days. The next challenge is to improve energy conversion efficiencies: While a silicon-based solar cell converts up to 20 per cent of the sunlight to electricity, Krebs and his team only get just under 1 per cent out of their air-stable polymer solar cells. At the same time, they had to find a solution to the main problem with solar cells: Unlike the human eye they do not allow for the fact that daylight varies in strength to the extreme – the light is up to 40 times stronger on a bright summer's day compared to a grey winter's day.

CORN CAN MAKE SOLAR CELLS ENVIRONMENTALLY FRIENDLY

Scientists are also working to develop materials with less environmental impact – "so that one lives up to one's responsibilities and the benefits are not outweighed by the negative impact," as Frederik Krebs puts it. The solar cell itself is so small that it does not pose any significant environmental problem – it is the polymer substrate carrying the cell which is problematic. Conventional plastic is very slowly degradable and can survive for hundreds or thousands of years in the countryside. Risø is therefore experimenting, among other things, with polylactic acid in an attempt to create a plastic material which is more quickly degradable and which is compostable, i.e. which rots like food when exposed to 65 degrees in a municipal biomass plant. Polylactic acid is made from corn and is not appreciably more expensive as a material – the challenge is producing an alloy which is just as strong, useable and cheap as conventional plastic so that the solar cell becomes 100 per cent biodegradable.

The environmental friendliness of the polymer cells is just one of the aspects which Risø's scientists are hoping to improve. The team has received a total of 25 million Danish kroner for a large-scale development project. The ambition is to improve the process, stability and energy conversion efficiency and to develop the polymer cells to a level at which they become attractive to industry. Initially, the cells can be used in calculators, egg timers and electronic display signs in shops which are currently powered by small batteries or cells based on the far more expensive amorphous silicon.

Solar cells which have not yet been fitted into panels. Risø's solar cells are cheap. Now they must be made more efficient before they can compete with other solar cell technologies.

In the longer germ, the ambition is for the technology to be used for energy production as such.

"And I very much hope that this will be in my lifetime," says 38-year-old Frederik Krebs.

Which is certainly realistic, according to Peter Sommer-Larsen. He points out that both Greenpeace and the European Photovoltaic Industry Association believe that solar cells will become so cheap and efficient that they will cover approx. 3 per cent of global electricity demand by 2025 – and that the generation of solar energy will employ more than three million people. Even people who are less directly involved believe in the technology: At the beginning of the millennium, an EU white paper set out the target that 1 per cent of the European electricity consumption would be covered by solar cells by 2010. This target was realised by 2007, not least thanks to considerable German investments in solar energy. Germany and Japan are the world's largest manufacturers of solar cells: Germany has a dedicated distribution system and has subsidised the energy heavily. Capacity corresponds to more than 30 peak watts per capita, compared with 0.5 peak watts per capita in Denmark.

SOLAR CELL HATS AT ROSKILDE FESTIVAL

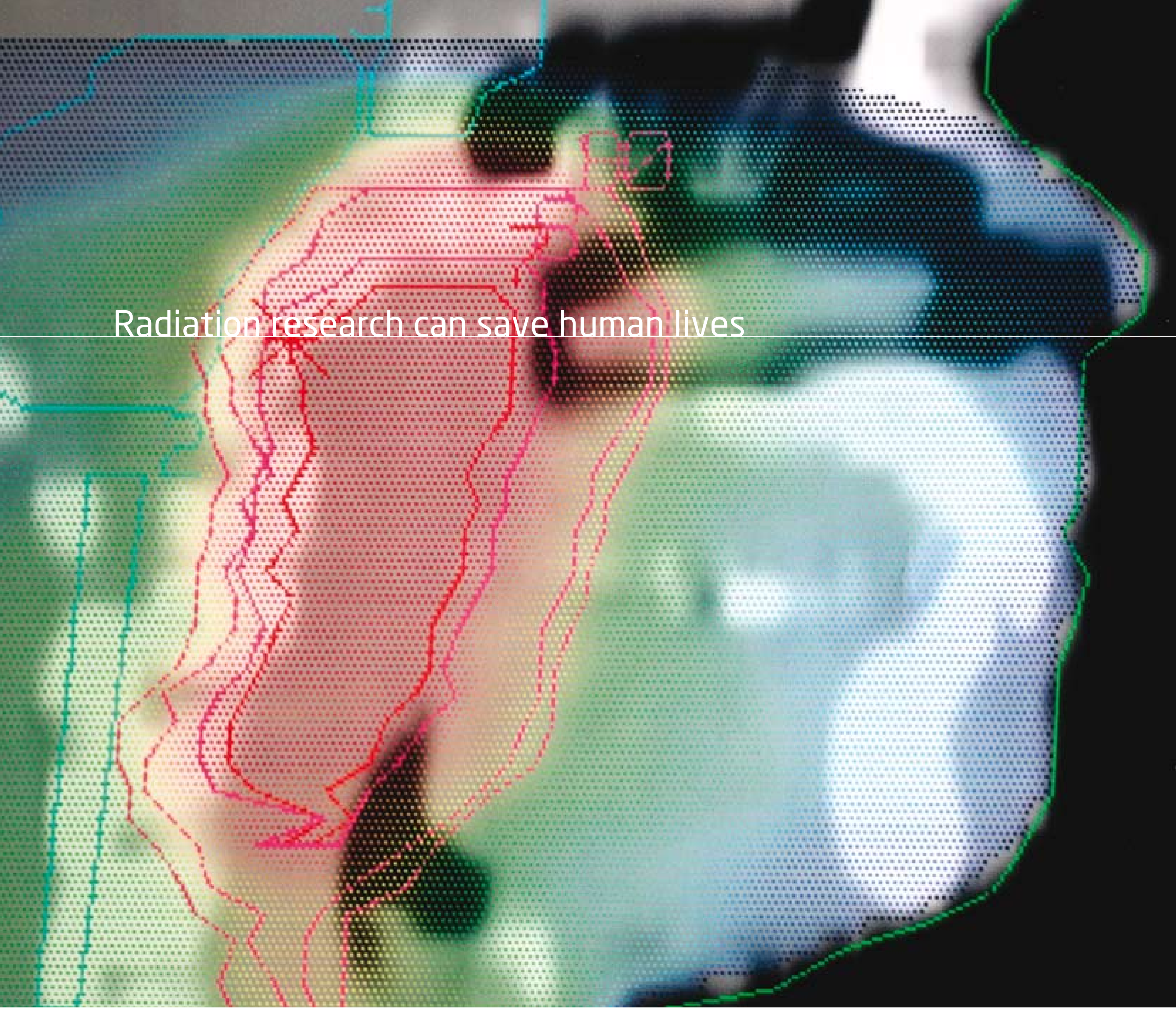
However, Risø scientists are in no doubt that the strong focus on climate change and the need to reduce CO_2 emissions will spur investments in solar cells around the world, also in Denmark. Especially since further development will mean that the new polymer technology will become far cheaper and almost as efficient as the first and second-generation solar cells which, at the time of the Risø anniversary, make up virtually the entire world market. In other words, Risø's experts can help to ensure that Danish solar energy will very soon be able to compete with Germany and Japan, even though these two countries have clearly been a lot quicker off the mark in this field. It is a clear aim of the large-scale development project that the technology should be able to compete on market-like terms as soon as possible. The 25 million Danish kroner of project funding comes both from the Danish Council for Strategic Research, from Risø's own coffers, and also from Risø's collaboration with three companies: EnergiMidt, the plastics group SP Group A/S and the printing business Mekoprint, which is based in Støvring.

Mekoprint was also involved in the decision to test the Risø solar cell on the public for the first time at the Roskilde Festival in summer 2008. Handing out a couple of thousand hats to festival-goers aims to demonstrate how you can listen to a radio powered by polymer solar cells. Both the radio and the solar cells can be built into a hat. What the solar cell experts fear most about this marketing initiative is that the festival might be as rainy as it often has been in the past. If so, people won't stop telling Frederik Krebs and the other scientists how the sun basically never shines in Denmark.

What you didn't know about solar energy

- Solar cells currently generate approx. 5.8 gigawatt worldwide (55 per cent is produced in Japan, 35 per cent in Europe and 10 per cent in the USA). This corresponds roughly to Denmark's total power consumption. In the past couple of years, solar energy has been the fastest-growing renewable energy source, yet it still accounts for only 0.4 per cent of the global energy supply.
- First-generation solar cells – silicon-based – account for approx. 90 per cent of the world market. The rest of the market is made up of second-generation thin-film solar cells. Third-generation polymer solar cells are, as yet, not produced for the commercial market.
- In 1995, the price of a 1 kW unit was 7,000 US dollars. By 2000, the price had halved, but then stagnated for a number of years due to a lack of supply. At the time of writing, the price is again falling, and a price of 1,000 US dollars is forecast for 2015-2020, translating into a payback time of just 10 years. Environmentally speaking, solar energy is also becoming more efficient – production involves fewer resources and lower CO_2 emissions.
- Solar cell output is measured in peak watt, Wp. An optimally sited 1,000 kWp solar cell unit generates an average of 850 kWh a year in Denmark and 1,800 kWh a year in southern Europe.
- If you took six places in the sunniest parts of the world, for example the USA, Africa, the Middle East and Australia, and covered an area of 100 x 100 square kilometres in each place, you could supply the entire world population with energy.
- There is no country in the world where more solar energy does not fall on the road network than is consumed by the nation in general.
- If you wanted to supply Denmark with power from a single renewable energy source, you would have to cover Langeland with solar cells, Fyn with wind turbines, or plant the entire country with biofuel crops.

Sources: EPIA (European Photovoltaic Industry Association), Risø Energy Report 6, Peter Sommer-Larsen.



Radiation research can save human lives

THAT MORNING, ON MONDAY 28 April 1986, measurements were unusual. Risø's health physicists carried out routine measurements of the radioactive content of samples taken from the local area around the national laboratory, and that day the readings were worrying. The samples of grass and air were radioactively contaminated, and levels were higher than those usually seen by the scientists. A quick investigation showed that the radioactivity did not come from Risø itself, and after a couple of phone calls to colleagues in Sweden and Finland, it became clear that they could provide no explanation either. It was not until the evening that the mystery was solved when the Soviet authorities announced

Risø has developed new ways of ensuring that patients receive extremely precise doses of radiation. An aluminium oxide crystal is inserted into the patient and absorbs a small portion of the radiation. By exposing the crystal, you can read how large a dose of radiation has been received.

From the very outset, Risø's research into the development of nuclear power was conducted in partnership with research into how radioactivity spreads and affects the surroundings. Today, nuclear power is no more at Risø, but radiation research remains an important field.

that one of the reactors of the Ukrainian nuclear power station in Chernobyl had exploded and caught fire more than two days previously, on the night between Friday and Saturday. Emissions of radioactive isotopes continued for more than a week as the cloud of radioactive fallout drifted with the wind, and immediately after the Soviet announcement, Risø's radiation experts started intensive measurings, co-ordinating their efforts with both the Danish radiation authorities and the Danish Civil Defence.

"Initially, it was particularly important that contamination of the grass be monitored as it was just about the time of year where the cows were let out to grass. Dairies from all over Denmark sent milk samples to us to make sure that the milk had not been contaminated," recalls Benny Majborn, Head of the Radiation Research Department.

Even today, a few countries still require a special certificate from his department at Risø before they will allow dairy imports from Denmark. But really, this should not be necessary as Risø's monitoring at the time soon showed that the radioactive fallout would result in only insignificant radiation in Denmark – doses of less than 5 per cent of the natural background radiation to which we are exposed in the course of a year. Nevertheless, Risø's scientists went into action exactly by the book. The original plans for the institution meant that not only should Risø be the locomotive bringing nuclear power to Denmark, with that task came a need for a range of other expertises. Not least a need to understand how radioactivity can spread and affect the natural environment and the human body.

It was essential that Risø should be able to advise the national authorities in the event of radioactive contamination of the environment, our food chain and the population caused by emissions from a nuclear power station or a nuclear attack. Radiation research was thus one of the first fields to be established at Risø. By 1956, before the construction of the first buildings for the nuclear test plant, health physicists were sent out to the small peninsula near Roskilde to measure the natural background radiation in the area, so that these measurements could later – like on that unfortunate morning in 1986 – be used to compare with changes in radiation levels.

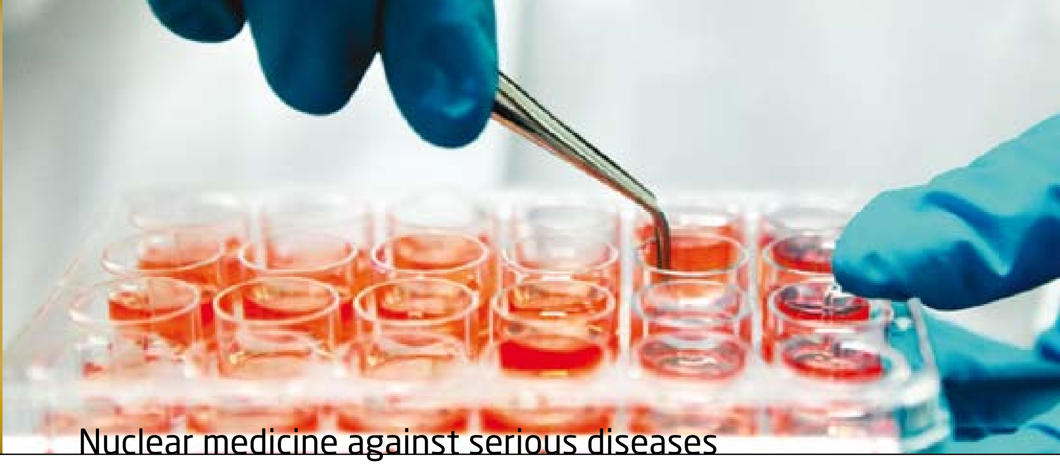
To this day, one of the Radiation Research Department's key roles is to form part of the Danish emergency management service in case of a radioactive contamination. Thanks to radioecological research, health physicists are now able to accurately describe how radioactive substances can spread with the wind and water and migrate in the biological systems, entailing a risk of contaminating our food chain in the event of, for example, an accident at a nuclear power station in a neighbouring country.

ONGOING STUDIES OF THE THULE ACCIDENT

One of the greatest challenges to ever face the centre's radiation scientists was the Thule accident in 1968. On the afternoon of Sunday 21 January, an American B-52 bomber carrying four hydrogen bombs crashed onto the sea ice north of the US Thule Air Base in northern Greenland, contaminating the area with plutonium. Some dispersed with the smoke from the dramatic fire, some remained on the ice and yet some sank to the bottom of the sea as the plane holed the ice on impact. Even though the extent of the damage was primarily investigated by the US military, Risø was soon involved in the work. When the Danish representatives arrived, the first measurements had already been made by the Americans, but further measurements were needed to ensure that neither the Greenlanders nor the approx. 850 Danes working at Thule Air Base had been contaminated by the plutonium dispersed by the violent fire.

Even though both the US military and Risø's health physicists concluded at the time that very little contamination was found beyond the accident site, where only US personnel were working, a number of questions were raised in the political aftermath and through the persistent attention devoted to the incident by the Danish media – for who could actually be held liable for the accident? Was Denmark informed by the USA sufficiently quickly? And were the health physicists' technical assessment of the scope of the accident trustworthy?

For this reason, the Thule accident has had a direct impact on the work of Risø's scientists ever since, for example in the form of repeated investigative expeditions to Greenland where measurements are still being carried out in collaboration with the Greenland authorities. Similarly, Risø has on several occasions since the Chernobyl disaster dispatched staff to the site to collect samples and to establish how to reduce contamination. Such investigations are all part of Risø's international commitment and sharing of scientific knowledge with international colleagues.

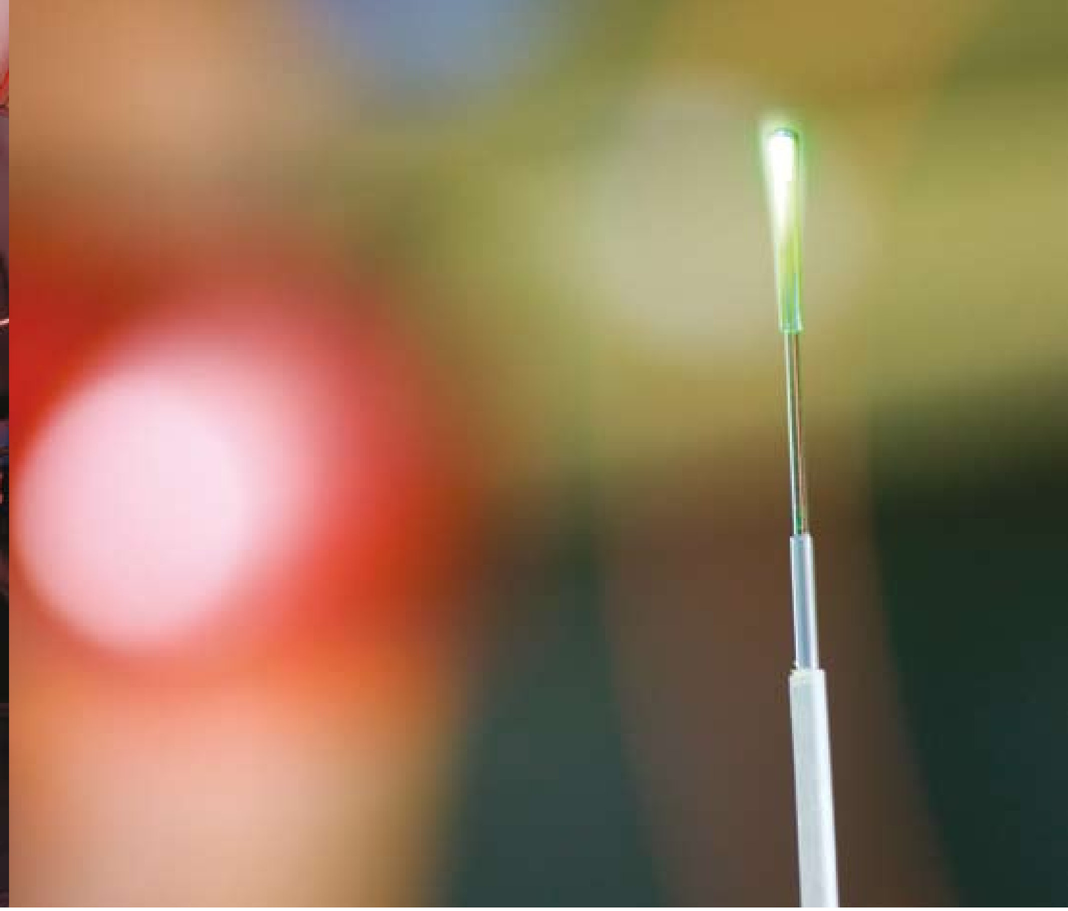


Nuclear medicine against serious diseases

Research into nuclear medicine at Risø's Hevesy Laboratory plays an important role in the fight against cancer at Danish hospitals. However, in addition to using radioactive tracers to identify and treat cancer, nuclear medicine can also be used to treat other serious and widespread diseases. For example, the techniques which have been developed can be used to examine the blood circulation in patients with arteriosclerosis as an essential tool in the fight against, not least, cardiovascular diseases which - despite a fall in recent years - remain the second-most frequent cause of death in Denmark. Every fifth death in Denmark is caused by cardiovascular diseases.

Another important category of disease which nuclear medicine research is helping to fight is diseases resulting in brain dysfunction and dementia. Tracer techniques can be used to analyse the number and activity of receptors in the brain. Within this area, the Hevesy Laboratory is working closely with hospitals and the pharmaceutical industry. For example, scientists are working closely with the pharmaceutical company GE Healthcare to develop a method allowing a measurement of whether patients are developing Alzheimer's, allowing earlier diagnosis of the disease than is possible today. The development of the disease can be slowed down by means of medicine, but it cannot be cured.

Alzheimer's is a disease which typically develops gradually over months and years, and for this reason being able to identify the disease early can be of crucial importance to helping individual patients. Alzheimer's causes the nerve cells in several areas of the brain to slowly deteriorate. It is estimated that Denmark has approx. 15,000 new cases of dementia a year. All in all, a total of 70,000-80,000 people in Denmark are believed to suffer from dementia, with more than half of all cases being caused by Alzheimer's.



ACCURATE DOSES OF RADIATION

An area in which Risø's Radiation Research Department is enjoying international recognition and has been leading the way for many years, is within research in and the development of methods for dosimetry, i.e. the area of health physics concerned with measuring and calculating radiation doses. The department has, for example, developed an apparatus for measuring the so-called optically stimulated luminescence which can be used for both dosimetry and for dating geological sediments and archaeological artefacts, for example, ceramics. The apparatus is still being developed and is being sold to research and dating laboratories worldwide.

As a new development, the department is also working closely with Danish hospitals on the use of dosimetry methods used to determine and verify radiation doses in connection with cancer therapy. For this purpose, Risø's scientists are using a very small dosimeter mounted at the end of an optical fibre cable. The fibre is inserted into the patient, allowing the radiation dose to be measured in a specific place in or outside a tumour with a view to verifying whether the patient is receiving the right dose.

Today, most of Risø's activities within radiation research are divided into three areas. In addition to radiation physics and radioecology, activities include work at the Hevesy Laboratory, where the Risø scientists produce and use radioactive isotopes to develop medical diagnostics and treatment methods. An area of activity also referred to as nuclear medicine. The Hevesy Laboratory was inaugurated in 2005. It is named after the Hungarian George de Hevesy, who received the Nobel Prize in Chemistry in 1943 for his discovery of how radioactive tracers can be used to study chemical processes in biological systems, including the human body.

Optically stimulated luminescence (far left) OSL measures how much radiation a cancer patient, for example, receives. By means of a probe (left) a tiny grain of a special material is placed near the tumour to be radiated. The grain absorbs some of the radiation. When illuminated, it emits light which can be used to determine how much radiation it has received.

Work with tracer techniques, like radioecology, stretches right back to the early days of Risø. Actually, this field of research can be traced back to the 1930s when Hevesy worked in close collaboration with Niels Bohr at the Niels Bohr Institute in Copenhagen. So, naming the new Risø laboratory after the Hungarian scientist was a very natural choice. But, of course, Risø first had to ask Hevesy's descendants for permission to use his name. The department therefore wrote a letter to Hevesy's eldest daughter, who lives in California, and the reply came swiftly – and even in perfect Danish. The family was delighted that Risø wanted to name the laboratory after Hevesy, and also wanted very much to be represented at the inauguration ceremony.

"We thought that perhaps a few representatives of the family would attend the ceremony. But actually no less than thirteen family members arrived, including three of Hevesy's own children who regarded Niels Bohr as an uncle," Benny Majborn recounts.

The activities engaged in at the Hevesy Laboratory basically stretch right back to the beginning of Risø. Even then members of the Atomic Energy Commission, which at the time was Risø's governing body, predicted that future nuclear research would not only be about energy, but also to a very large extent about medicine. As chairman, Niels Bohr deserves special credit for such foresight.

"Before his death he predicted that molecular biology would be the next great step within research. This says something about the calibre of Niels Bohr. And we are proud to be here today, carrying on a noble Danish tradition started by Bohr and Hevesy," says Lars Martiny, who is head of the Hevesy Laboratory.

NEW WAYS OF DIAGNOSING AND TREATING CANCER

The Hevesy Laboratory primarily works to develop new methods, tracers and tools which can be used to trace and diagnose cancer. In addition, the scientists are working to develop and produce new radioactive substances which can attack the cancer. Last, but not least, the Hevesy Laboratory produces radioactive tracers which are used in PET scanners at Danish hospitals.

PET scanning is a medical imaging procedure which involves injecting radioactively labeled tracers into the body of a patient prior to the scan. Put briefly, the fundamental technique of using tracers involves attaching the radioactive isotopes to a so-called target molecule which either binds to particular cells, for example a cancer cell, or which naturally concentrates in particular types of tissue. Tracers can be used to identify both where the cancer is – as in a PET scan – or to directly attack the cancer, depending on the isotopes used.

The OSL grains are approx. 0.1 mm in diameter. They can be kept and read several times. These are the test holders. Each of the round holders in the wheel holds 100 grains.

"Some isotopes are good for finding out where the cancer is, while other isotopes are good at killing it," Lars Martiny explains.

Even though a few hospital PET centres can produce and develop their own radioactive tracers, the demand today is so enormous that they are not always able to keep up. This is where Risø can help. The radioactive tracers used for tracer examinations – and for Risø's own research – have been produced at Risø since the 1960s. Initially, production took place in the DR2 test reactor and then in the DR3 test reactor. However, after the closing-down of the reactors and the subsequent establishment of the Hevesy Laboratory, a so-called cyclotron – also referred to as a proton pistol – is located in a bunker underneath Risø's lawn and it now produces the radioactive substances needed for research.

"If we need to produce for more patients at the hospitals, we start production between 4 and 5 am and dispatch by 7 am," Lars Martiny explains. "Between 7 and 8 am we carry out quality control, and by 8 am we can fax the hospitals to let them know whether it is safe to use or not."

Once Risø has released the substance for use, it is injected into the body of the patient via the arm and carried round by the blood. Half an hour later the scan can take place.

"We employ physicists, chemists and pharmacists. We have no scanners, so we are dependent on collaboration agreements, for example on our close collaboration with the Panum Institute, Copenhagen University Hospital and other large hospitals," says Lars Martiny. Like Benny Majborn, he believes that Risø's radiation scientists will be devoting more and more of their time in future to developing health-related technology.

"We are thrilled to be doing research which can help save human lives," says Benny Majborn.

Radiation research for medico, geology etc.

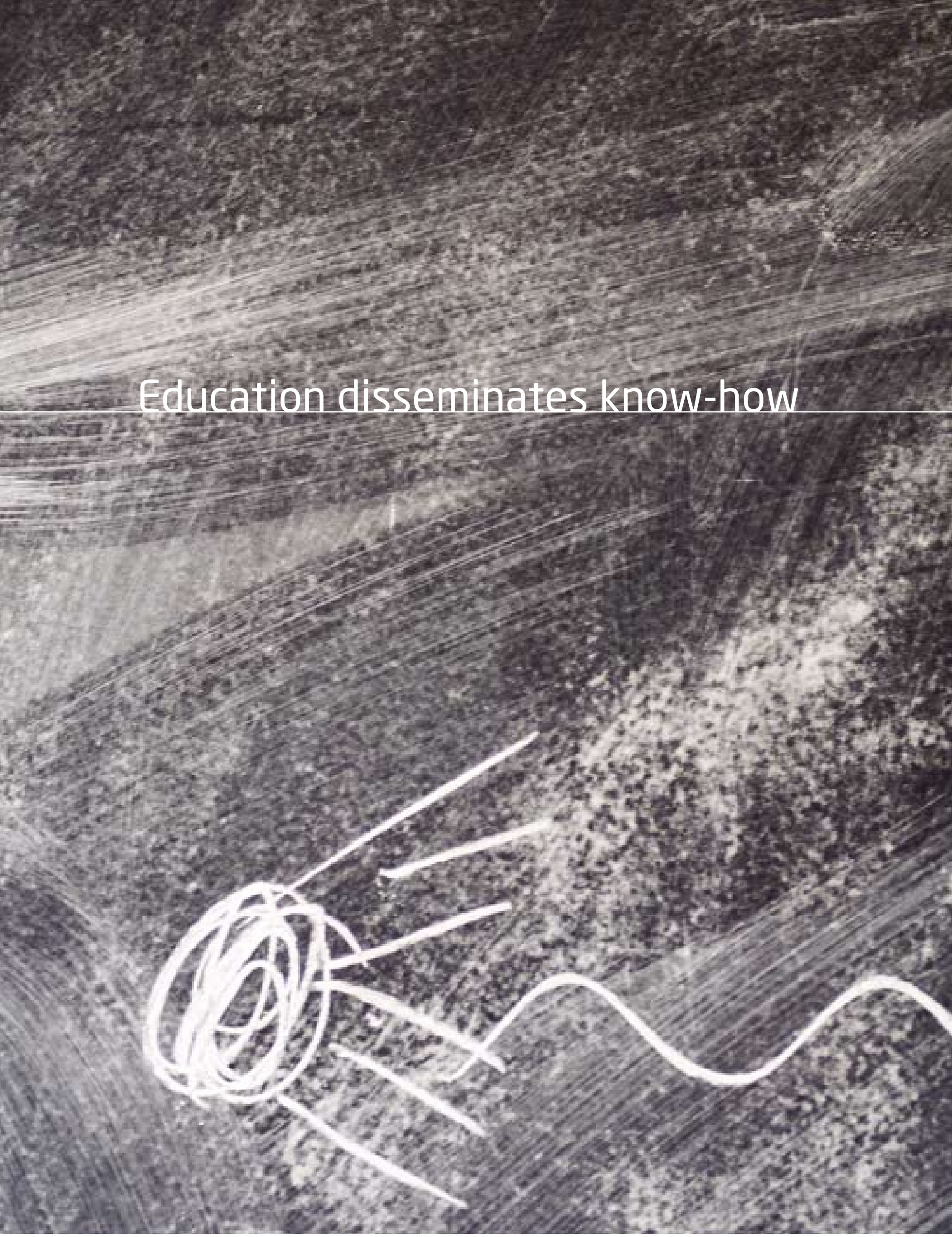
Risø's radiation scientists also engage in industrial dosimetry used in connection with sterilising medical equipment. The challenge here is to determine the exact dose of radiation for the microorganisms to be killed without damaging the product.

However, radioactive isotopes are not only used for medical purposes. The department also produces technical isotopes. Customers include plumbing, ventilation and heating firms looking for leaks in central heating systems. Thanks to the radioactive isotopes, they can identify the leak.

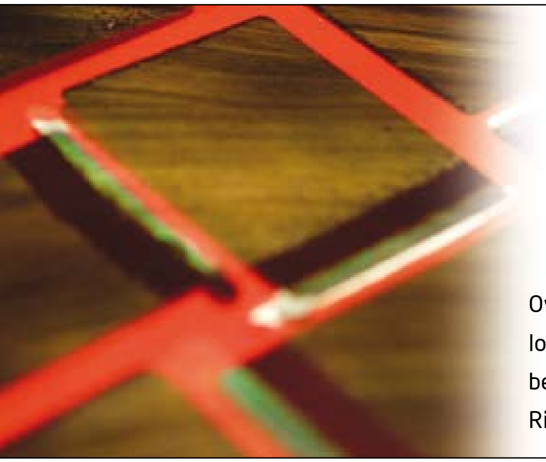
Other professionals also benefit from the radiation research. For example, the radiation scientists can assist both geologists and archaeologists in connection with the dating of geological sediments or archaeological artefacts. A piece of pottery or a sediment which has been protected against daylight until the time of finding will have absorbed a certain amount of radiation energy during this period. Risø has developed a luminescence dosimetry method which can determine how much radiation energy such samples have accumulated. In this way, it is possible to calculate how long the samples have lain undisturbed.

By measuring the accumulated radiation in a brick or another suitable material, it is also possible to determine the levels of radiation to which the residents in a house or a region have been exposed following a nuclear accident. This method was, for example, used after the Chernobyl disaster. The dating of geological sediments on Earth is performed by many laboratories around the world using equipment developed by Risø. Risø is currently investigating the possibility of more exotic applications, i.e. the dating of sediments on Mars.

Education disseminates know-how



AN EXCITING INTERNATIONAL, interdisciplinary and young workplace. This is how Risø has often been described by PhD students and others who have had the chance to complete part of their studies at the national laboratory on the shores of Roskilde Fjord. Teaching is no new activity for Risø's scientists, but with its new status as national laboratory for sustainable energy at the Technical University of Denmark, the way has been paved for Risø to have an even greater say in educating the energy technology experts of tomorrow. Up until 2007, Risø was a government research institution charged with carrying out strategic research, i.e. research paving the way for finding solutions to challenges facing Danish society.

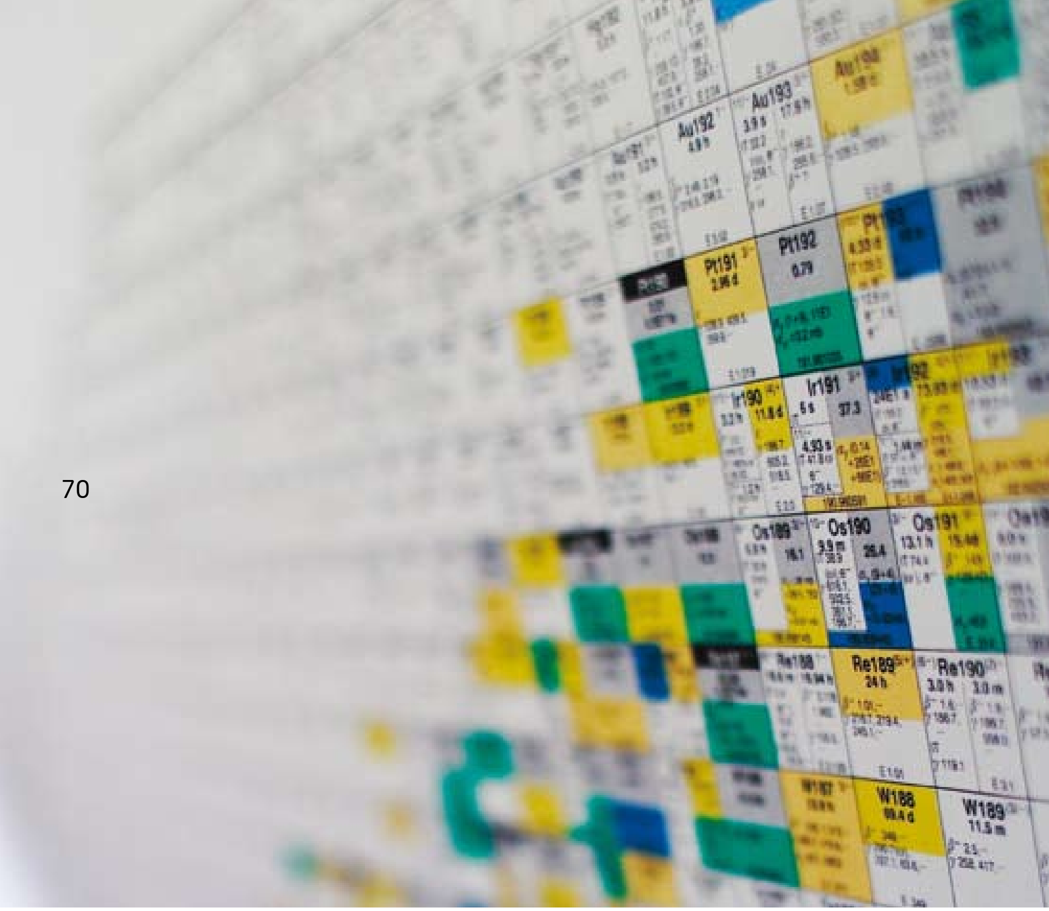


Over the years, Risø has welcomed a large number of project students. Following the merger with the Technical University of Denmark (DTU), it has become possible to offer new study programmes which draw specifically on Risø's special competencies and working method.

The scientists were not obliged to do any teaching, but they have nevertheless always devoted some of their time to educating scientists and to supervising students working on specific projects. Risø scientists have thus played the role of co-supervisors on many PhD projects. Postgraduate students have been able to write their theses or other projects at Risø, and over the years many students have undertaken research-related jobs as student assistants. However, the flow has not only been one way; many Risø scientists have also been involved in teaching activities at the universities as lecturers or affiliated professors, while also contributing in various ways to the supplementary training of employees in the private sector. What characterises Risø's offer to PhD students is the fact that they are involved in day-to-day activities and take part in the research activities on an equal footing with the scientists.

"At Risø we take a very interdisciplinary and strategic approach to our work. We also engage in basic research, but always with a specific objective in mind and always in groups. At Risø, students learn to work in a team and towards a particular aim, with clearly defined roles and, not least, with good contact to the business community," says Head of Programme Luise Theil Kuhn, who is head of Risø's coordination group for teaching. Students also have access to unique experimental equipment and facilities which are not part of the standard set-up at most educational institutions. At the same time, many experience a high level of close communication, both with their research colleagues and with partners in the private sector. This is one of the reasons why Risø enjoys such a good reputation among students.

"Risø is an exciting place to work, and a place where I am proud to be working. So much groundbreaking and visionary research goes on here. It is also a young workplace with lots of PhD students. The days never felt routine-like, there were always new challenges to tackle, and we were always encour-



aged to network with people from other fields," says Thomas Frank Petersen, who completed his PhD at Risø in 2007.

The reputation Risø enjoys among students has shone through in international evaluations. In 2006, when Risø was included for the first time in the research and management consulting company Universum Communications' annual image survey of the requirements and wishes of engineering and natural science students for their future workplaces, it shot straight to eighth place out of more than 100 enterprises. Never before had a new enterprise gone straight into the Top 10 in Universum's many international surveys, and it resulted in a Highest Flyer prize for Risø. The following year Risø came third in the same category in the image survey. The results reflect expectations which are very much in line with the results from a similar Universum survey among more than 4,000 university graduates. In this survey, which was conducted in 2006, Risø was ranked number ten among the most attractive workplaces for university graduates with a background in the natural sciences.

MSC IN ENGINEERINGY (SUSTAINABLE ENERGY)

Following the merger with DTU, Risø has even more to offer students. For example, a new and highly topical MSc in Engineering (Sustainable Energy) starts in autumn 2008.

"The MSc in Engineering (Sustainable Energy) will produce graduates who make a real difference by contributing to solutions to some of the most important and pressing challenges of our time within the fields of climate and energy. The new MSc programme will be taught by scientists who are leading the way within their fields, and who know what is interesting to industry and to society because Risø has always had to bear this aspect in mind. Consequently, and on account of Risø's excellent reputation as a research institution, the study programme has naturally attracted a great deal of attention – not least from abroad with more than 60 students expressing an interest," explains Peter Meibom from the Systems Analysis Department, who is Programme Coordinator of the new MSc programme.

Luise Theil Kuhn has been responsible for combining all the various competencies at Risø into a coherent and interdisciplinary study programme.

"The study programme is very relevant and topical, but also highly interdisciplinary, and it will place heavy demands on the students' background qualifications and their ability to acquire new knowledge about other specialist fields. In this context, Risø's research environment should be ideal," she says.

Collaboration with industry and the high quality of the research conducted at Risø have also resulted in a new elite study programme within fuel cells and hydrogen which will be offered by Risø from autumn 2009 in collaboration with the physics and chemistry lines of specialisation at DTU and with Topsoe Fuel Cell as industrial partner. The study programme will be taught by internationally top-class scientists and experienced teachers who will guarantee the high academic standards of the new programme.

"These are special postgraduate study programmes for the really talented students. We want to nurture and challenge these students in particular," Luise Theil Kuhn explains.

The many new students who will be moving around at Risø will have their central base in the Information Service Department, in a light and airy study environment with PC workstations. Here they can get IT support and help with information searches. They can find inspiration in books and journals. Or they can take a break in the cosy corner or the nearby Friday Bar conceived by PhD students a few years ago. But what is most important is still the contact which they will have with Risø scientists in their laboratories. And the pleasure of that will be mutual:

"Students have always and will also in future provide real and valuable input for the projects, and that is of tremendous benefit for the working environment and the dynamics out here," says Luise Theil Kuhn.

The reactors survived nuclear power

AS IT STANDS THERE, round and glowing in the early spring sunshine, Risø's pensioned-off test reactor looks more like a giant grain silo clad in corrugated metal. But don't let that fool you. For there can be no doubt that the largest test reactor (DR3) on the peninsula in Roskilde Fjord has been at the centre of many advanced experiments and technological achievements since it was first commissioned in 1960. Today, both DR3 (2000) and its two smaller siblings DR1 (2001) and DR2 (1975) have long since been decommissioned. But in their active days, Risø's three test reactors were in many ways the most tangible symbol known to the general public of the many activities carried out there. So much so

The building which housed Risø's DR2 reactor. This was closed down in 1975, while the DR3 and DR1 reactors remained in operation until 2000 and 2001, respectively.
Below: Top of the fuel element for the DR3 reactor.

Risø was built around three nuclear reactors, and even though nuclear power faced quite a lot of opposition in Denmark, the reactors secured Risø a place on the world map of research institutions. The largest reactor and the materials research for which it was used have proved particularly valuable.

that employees from other fields of research could get quite annoyed from time to time at being asked what on earth they were doing out at the 'nuclear station'.

However, it is actually not so surprising that the reactors and the associated activities have defined a large share of the history of Risø as a research institution. From the outset, the reactors were the backbone of Risø, and long after the Danish Parliament said a final No to nuclear power in 1985, the reactors, and especially DR3, were a very important part of Risø's activities. Throughout most of the reactors' lives, Risø had a substantial income from the production of silicon for semiconductors and isotopes for medical research, and several of the R&D areas in which Risø is today making its mark internationally have their origins in the physics and materials research conducted around the reactors.

One example is the development of materials for fuel cells. This started with basic studies of the properties of solid electrolytes. Another example is Risø's basic materials research, which is largely built around the neutron scattering experiments carried out at DR3. However, the reactors have also rubbed off on other areas. The need to know how radiation will spread with the wind in case of a nuclear leak created the basis for a research group within meteorology. Knowledge of wind conditions near the surface of the earth later led to Risø's wind energy research.

From Risø's opening in summer 1958, the fundamental aim of the centre was to ensure that Denmark kept abreast of international developments within the peaceful utilisation of nuclear technology. The dominating field was nuclear power, and in this context the reactors – and the many scientists working there – were to drive the development of nuclear power stations on Danish soil.

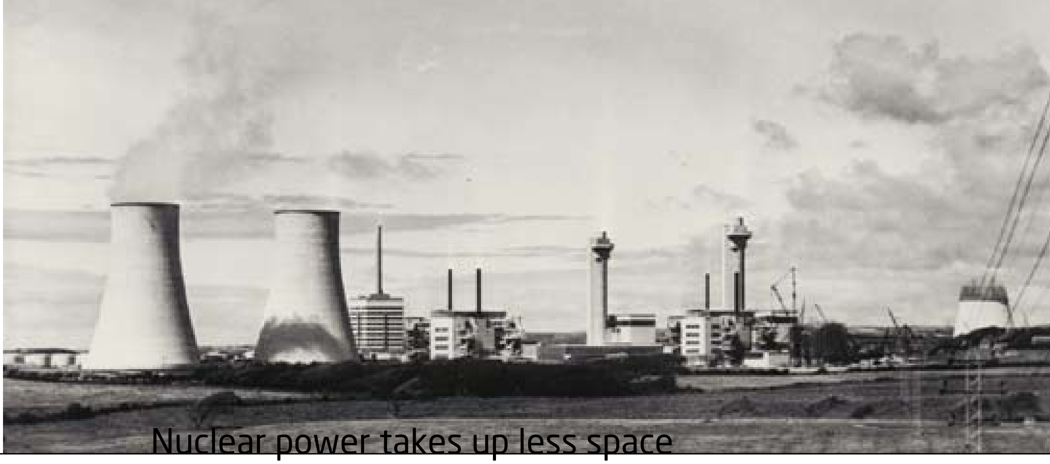
Research into nuclear power was to both strengthen our international reputation as a research nation – after all Denmark was home to the highly acclaimed nuclear physicist and Nobel Laureate Niels Bohr – and ensure Danish energy supplies in the long term. A challenge which many people at the time thought needed solving if we were to maintain our high standards of living. In terms of energy supplies, Denmark was at the time extremely vulnerable in that we were almost totally dependent on imported coal and oil. Those at the end of the table in this political and strategic process were, in fact, Niels Bohr himself together with Hans Henrik Koch, Permanent Undersecretary with the Danish Ministry of Social Affairs.

About three years before Risø's inauguration, the Danish Parliament had appointed an Atomic Energy Commission chaired by the Nobel Laureate. The commission, which was established in December 1955, managed – after a lot of hard work on the part of especially Bohr and Koch – to convince the Social-Democratic Government that not only was it necessary to focus on nuclear power, it was necessary to invest in nuclear power to an extent so far unheard of in the Danish research community. Risø grew and grew, and budgets increased until the operating budget in 1960 stood at more than 30 million Danish kroner a year. By comparison, the funding for Danish technical research totalled about 100 million Danish kroner in the same year.

MAJOR INVESTMENTS AND CHANGES

In 1957, the first two reactors – DR1 and DR2 – were bought from the Americans. Moreover, there were plans to develop a special Danish type of reactor, one which could utilise naturally occurring uranium. The hope was that the uranium reserves in Greenland would make Denmark self-sufficient in energy. Finally, some members of the Atomic Energy Commission wanted a third – and larger – reactor which, unlike the light-water reactors DR1 and DR2, was based on heavy water and thereby more suited for unenriched uranium. This last purchase gave rise to what was for the Atomic Energy Commission a very heated discussion. The critics took one look at the growing budgets and thought that there was really no need for three reactors. The proponents – including Bohr – maintained that if Risø was to make its mark internationally, DR3 was very much needed. Bohr's side won, and DR3 came to Risø. This should later prove a very worthwhile investment.

The discussion about DR3 was a forewarning that the considerable levels of funding going to Risø were gradually becoming a bit too much for other parts of the Danish research community. The early 1960s were dominated by an intensifying discussion, both outside and within the Atomic Energy Commission, of whether the institution could take up so much of the available research funding in Denmark as well as so much technically qualified manpower for the sole purpose of developing a basis for nuclear




Nuclear power takes up less space

The world's first civil nuclear power plant was a Soviet installation. On 27 June 1954, the nuclear power plant in the Soviet research town of Obninsk started generating electricity for the local grid. The reactor had a capacity of just 5 MW, less than the capacity of one of today's large wind turbines. In 1956, the first commercial nuclear power station opened in Sellafield in the UK (with a capacity of 50 MW and subsequently expanded to 200 MW), and the following year, the first nuclear power station started operations in the USA.

Throughout the 1960s, 1970s and the first half of the 1980s, the use of nuclear power increased dramatically, not least due to the oil crises. However, following the accident at the Three Mile Island nuclear power station in the USA in 1979 and the Chernobyl disaster in 1986, the building of new reactors almost came to a standstill. This trend persisted throughout the 1990s, among other things because low natural gas prices meant that investors were hesitant to make the very considerable investments required in connection with new nuclear power stations. Existing power stations were, however, made more efficient, and today the world's nuclear power stations almost supply twice as many kWh as they did in 1986. Nevertheless, nuclear power (in 2005) accounted for only approx. 15 per cent of the global electricity supply, which is slightly less than in its heyday from the mid-1980s to the mid-1990s.

Increasing focus on the greenhouse effect and new reactor types has raised the question of whether nuclear power can come to play a significantly bigger role in the mix of energy sources which will be taking over after oil. However, the International Energy Agency believes that even with growth in capacity at the world's existing – and new – nuclear power stations, the rate of increase is unlikely to follow the general increase in the global electricity production, and nuclear power will come to play an ever diminishing role in the global energy supply.

Source: IAEA, IEA

power in Denmark. Moreover, the development of a special Danish reactor type was not progressing as swiftly as had been hoped for, and in 1964 these activities were abandoned at Risø. At the same time, it was decided that the institution should serve a broader purpose. The nuclear energy activities at Risø were now supplemented by other research which could make use of the reactors. However, it was made clear from the outset that Risø should not be a centre for basic research only. Basic research and technological research were to go hand in hand, and Risø should engage in basic research, but always with a specific objective in mind.

SUITABLE FOR RESEARCH

The three test reactors were used for different purposes. Until the decommissioning of DR1 in 2001 – the last of the three reactors to be closed down – it was used exclusively for teaching purposes. DR1 had a maximum thermal capacity of 2 kW, corresponding to an electrical hotplate, and was so small that it could be turned on and off in just a few minutes. You could turn it on in the morning, and the last person to leave at the end of the day had to remember to switch off the lights and the reactor.

While the smallest member of the reactor family thus had a very clearly defined function, there was more initial overlap between DR2 and DR3. Later on, most of the advanced basic research activities were transferred to DR3, while DR2 was primarily used for more specific industrial assignments, such as the production of isotopes for the pharmaceutical industry and various types of tracing, for example of leaks in building structures.

It is the work involving DR3 which has really placed Risø on the world map of research centres within reactor technology and a number of derived fields of research. DR3 was primarily used within four areas. One of them was experiments involving reactor materials and fuel rods for reactors. These activities initially took place in collaboration with both B&W and Helsingør Shipyard and Machine Shop, which were the chosen suppliers of reactor tanks and fuel rods, respectively, if Denmark was to have nuclear power. The fuel rod experiments were aimed at increasing efficiency with a view to improving reactor economy and reducing waste. These activities continued at Risø until 1990, latterly with international customers, typically power stations or nuclear safety authorities.

DR3 proved to be an excellent source of neutrons. This meant that some of the neutrons released during nuclear fission in the reactor could be extracted for use in both research and the production of special-purpose materials. One example of the latter was the production of doped silicon, which for a number of years was one of Risø's commercial successes. This work, which was primarily carried out in

Materials scientists at Risø are, among other things, seeking to develop new superconducting materials (far left) which work at higher temperatures than is possible today.
Superconductors can, for example, increase the profitability of wind turbines.

collaboration with Topsil A/S, involved neutron radiation of silicon. The radiation transforms some of the silicon atoms into phosphorus, increasing the conductivity of the semiconductor silicon manifold, which can be used, for example, in the manufacture of computer chips. In 1992, 30 per cent of the world's production of doped silicon for semiconductor production was made at Risø. Production originally took place at DR2, but was transferred to its big brother in 1975 when DR2 was closed down. The work continued at DR3 until it was closed down in 2000. Likewise, DR3 was used for testing bore samples from the subsurface of the North Sea. When the samples were irradiated, it was possible to determine the content of various elements. The knowledge could be used to determine the geological history of the subsurface, and thereby the likelihood of finding oil and gas. Finally, DR3 was, after the decommissioning of DR2, used extensively for producing isotopes for medical research, diagnostics and treatment.

It was not obvious from the start that DR3 would become such a good source for neutron research. Other test reactors round the globe boasted greater capacity and thereby more neutrons per second. More neutrons per second provide scientists with more data and thereby a clearer picture of what goes on within the substance being examined, but scientists at Risø compensated for this by developing methods of making the most of DR3's limited volume of neutrons. Their 'neutron optics' have subsequently been copied in other countries around the world.

The fourth important area of activity for DR3 drew very much on the expertise gained in connection with the work on neutron irradiation. That is materials research. When analysing how neutrons are spread against the materials, important information can be gained about atom positions and movements within the material. Risø has, over the years, embraced many aspects of materials research, from analyses of what happens in plastics when stretched, to answering questions such as why is it that plastic carrier bags become stronger when they are so full that the handle is about to fall of? – to developing ultrastrong magnets for industrial applications and conducting experiments involving superconductors capable of conducting current without any loss and potentially causing a revolution within all areas in which electricity is used today.

THE RESEARCH CONTINUES

Several of the fields of research that made use of the reactors are still active at Risø. One example is, in fact, research into superconductors. The special substances which can conduct electricity without any loss play a decisive role in the development of new energy technologies in which Risø is involved. A central example is the development of superconducting materials for generators in the MW wind tur-

Risø's three reactors: DR1 (right), DR3 (building from outside, far right) and DR2 (below). DR2 was closed down in 1975, while DR1 was still used for teaching purposes, and DR3 was an important instrument in Risø's research. The reactor was an excellent source of neutrons, which can be used for materials research.

bines of the future. Expectations are that generator weight and volume can be reduced to a third by using superconducting materials. Superconductors are also used for electric cables and play a decisive role in the development of possible future fusion reactors. Fusion is the process which creates the sun's energy, and to handle substances which are many million degrees hot in a fusion reactor, they must be kept in check by very powerful magnetic fields. Such fields can be created by means of superconductors. Superconducting magnets are already being used in, for example, hospital MR scanners and at large research centres such as the high-energy physics centre CERN in Switzerland, but must be cooled quite considerably to work. The aim is therefore to produce superconductors which work at higher temperatures and with improved properties so as to make the technology more economical. Neutron scattering experiments are still very important in this work. Today, Risø's scientists are therefore using neutron sources abroad to conduct their experiments.

The fact that the research involving Risø's reactors still plays such an important role in the institution's activities at the time of its 50th anniversary could hardly have been foreseen back then in the 1970s when public opinion became more and more sceptical of the use of nuclear power on Danish soil. Already by the end of the 1960s, the post-war period's considerable enthusiasm for and praise of technological progress started to evaporate. This trend was seriously spurred by the hippie movement, by protests against the Vietnam war and the growing fear of atomic war as television brought more and more of the horrors of war live to living rooms in Denmark.

When the world was thrown into the first widespread oil crisis in 1973, it suddenly looked as if nuclear power might be welcomed in Denmark after all. The electricity utilities started to show an interest in nuclear power, and several nuclear power stations were planned. But public mood was against it. By 1976, popular protests against nuclear power had reached such heights that the Social-Democratic Government headed by Anker Jørgensen decided to postpone the final decision concerning nuclear power on Danish soil at least until a technological solution had been found for the safe storage of the radioactive waste from the power stations.

Having read the writing on the wall, Risø's scientists started to diversify even more, which meant that nuclear power came to play an ever smaller role in the institution's activities. Long before the Danish Parliament's final decision in 1985 to take nuclear power out of the Danish energy plan, Risø had already changed course so that ever fewer activities were concentrated on nuclear power, while more and more resources were devoted to research into alternative energy.

Still, the announcement that the precious DR3 reactor was to close was received with some sadness. And it was not exactly a group of employees in perfect agreement which was called to the Niels Bohr Auditorium at Risø to be told that the last reactor would close down in 2001. Today, the reactors are in the process of being decommissioned, but the activities which grew around them continue to play a role at Risø.

An era dismantled

DR1 was commissioned on 15 August 1957 as the first reactor in Denmark. It was also the last of the three reactors to be taken out of operation. DR1 was a so-called homogenous reactor in which the fuel was dissolved directly in light water. DR1 had a maximum thermal capacity of 2 kW, corresponding to that of an electrical hotplate. The decommissioning of DR1 was completed in 2005. DR2 was switched on for the first time on 9 December 1958. To make savings, operations were restricted already in 1963, and in 1974 it was decided to decommission the reactor the following year.

DR3 was a heavy-water reactor with a thermal capacity of 10 MW – by comparison the Barsebäck 1 reactor (which closed down in 1999) had a thermal capacity of 1800 MW. Ever since the mid-1970s, the reactor-technological activities have been in the process of being decommissioned at Risø. Following the closing-down of DR2 in 1975, the so-called hot cell plant (in which highly radioactive objects were handled) followed suit in 1989. The decision to close down the last two test reactors – DR3 and DR1 – was made in 2000.

In 2003, the Danish Parliament approved funding for a special institution – Danish Decommissioning – with specialist handling and decommissioning know-how to be established. The work is expected to take approx. 20 years. So far, DR1 has gone completely, while DR2 is being dismantled. DR3 has as yet not been dismantled, but the fuel has been removed, and the heavy water has been drained from the primary cooling system. The fuel has been sent to the USA in accordance with an agreement concerning the return of depleted fuel.

Source: Danish Decommissioning

Risø gets a grip on it all

"THERE WAS NO space for us anywhere, so we met in three on-site wooden pavilions next to the old reactor technic department. The views of Roskilde Fjord were absolutely glorious with the swans flying past like jumbo jets. The huts had electrical heating, so in winter if anybody left a bit of tea in their cup on Friday afternoon, it would be completely frozen when we arrived again on Monday morning. We really felt like pioneers, which I suppose we were at the time."

Senior Scientist Poul Erik Morthorst cannot help but smile when remembering the first couple of years in the Energy Systems Group at the end of the 1970s. It is now part of the Systems Analysis Department.

With the 1970s' energy crisis, car-free Sundays and chilly living rooms, energy planning and alternative energy sources made it onto the political agenda. For Risø, this meant the appointment of the Energy Systems Group, which assisted the Government with the first national energy plans. Today, the challenge is to design sustainable energy systems for the future.

The early pioneering days of the Energy Systems Group in its pavilions may now be part of fond memories, but 30 years later the group's activities remain more relevant than ever. Climate change and the desire to be less dependent on fossil fuels have strengthened the call for renewable energy, and this places considerable demands on the design of energy systems. Renewable energy must be incorporated into the energy systems in such a way that, for example, optimum use is made of the power generated by wind turbines, while at the same time ensuring that power continues to flow once the wind has died down. This very issue – maintaining the stability of an energy system which features an ever increasing share of fluctuating renewable energy sources, while at the same time ensuring that the energy consumed is as CO_2-neutral as possible – is at the core of the activities at the Systems Analysis Department.

BORN OF THE ENERGY CRISIS

Uncertainty about energy resources was the reason for Risø launching the Energy Systems Group. The Yom Kippur war between Israel and several Arabic countries in 1973 led to rapidly dwindling oil supplies, and prices shot up by 300-400 per cent. The energy crisis had arrived, and the power stations did not have enough oil to meet demand in Denmark. At the time, oil accounted for 90 per cent of the energy supply in Denmark. To conserve oil, a ban was introduced on travel in private cars on Sundays, and the interest in alternative energy sources took off. In 1976, the first political plan for the development of the energy supply in Denmark was presented. 'Danish Energy Policy 1976' took the oil

Solar cells and biofuels are expected to play an ever greater role in future energy systems. This was one of the conclusions in the Risø Energy Report 6 from 2007.

crisis as its point of departure, and the aim was to minimise the dependence on oil, in the first place by focusing on natural gas and nuclear power, and to a lesser extent on coal and renewable energies. However, the plans for nuclear power were soon put on hold and completely abandoned in 1985, as coal, gas and then – very gradually – renewable energy came to play a bigger role in the Danish energy supply in the following years.

The oil crisis demonstrated the need for more knowledge about energy sources and how to use them. A total of 50 million Danish kroner was appropriated to energy research, and the then Chairman of the Board of Governors of Risø, Erik Ib Schmidt, immediately launched into negotiations with the Danish Ministry of Trade to secure a portion of the funding for four projects – studying energy storage, wind power, fusion research and model calculations. The last project was to contribute to the work of the Government's new heating plan committee under the Ministry of Trade, which was to come up with a new heating plan for the whole country.

FOCUS ON INTERDISCIPLINARITY

The Ministry of Trade subsequently invited Risø to serve on a national steering committee for heat planning. The committee soon identified a need for more in-depth analyses of economic, technical and resource-related factors as well as the composition of the energy supply. This led to the establishment of the six-strong Energy Systems Group on 6 September 1977. Ove W. Dietrich from Risø's Department of Physics headed the project, but it was Bjarne Micheelsen, Head of the Department of Reactor Technology, who was the primary driving force behind the group. At the time, Risø had a number of research groups which were working on new technologies within alternative forms of energy. However, the Energy Systems Group was the first to span all the various fields of research at Risø, focusing on technology, economy, energy systems and the environment all at the same time.

"We realised that it was probably a good idea to have a number of analysts who could look at things across the disciplines and analyse how the technologies could be used, what this would cost and what the environmental consequences would be," explains the Head of the present Systems Analysis Department, Hans Larsen, who in 1980 took over the management of the group which then consisted of twelve academics, six economists and six scientific staff, i.e. engineers and physicists.

The purpose of the newly established Energy Systems Group was to project future energy demand as objectively as possible as well as the optimum mix of energy sources. Initially, considerable focus was directed at employment and the balance of payment and less on the environment. The tool was energy system analyses where various scenarios could be simulated in computer models.

Risø Energy Report

Risø has published its annual Risø Energy Report since 2002. The aim of the report is to advise on the best energy solutions for society and how Risø's research into sustainable energy sources can be used. The latest report, Risø Energy Report 6, was published in November 2007 focusing on the EU's two biggest energy challenges: To reduce CO_2 emissions by developing and implementing more sustainable energy sources as well as by ensuring the security of supply. Half of the fossil fuels consumed in Europe are imported, and this proportion is expected to increase to 65 per cent by 2030. The report presents a number of conclusions/recommendations, such as:

- Fuel cells are close to a breakthrough and should be used for more efficient energy conversion, for example to replace oil and gas-fired boilers in buildings.
- Denmark will be able to play a key role in developing flexible energy systems for the future.
- The solar cell technology is growing rapidly, but is still an expensive solution. Risø is working on polymer solar cells which are not as efficient as current technologies, but cheaper. Denmark could build up an industry within this field if it was adequately supported by the Government.
- Second-generation biofuel produced from plant waste could be ideal for the transport sector and for heating buildings. However, we need to study how biomass can be fitted into the energy system, not least in terms of finances and CO_2 accounts.
- Fusion energy offers tremendous scope as a CO_2-free energy source but the technology is still at the R&D stage. The first commercial fusion power plants are expected to be ready by 2045.
- Geothermal energy and wave energy offer potential and could, with suitable political incentives, play a role in the future energy supply.

The report is available at www.risoe.dtu.dk

There is a considerable need to reduce energy consumption both in our homes and workplaces. At the same time, more energy sources must be incorporated into the energy system in a sustainable way that also takes account of the climate. Risø is developing tools that can be used for this purpose..

By increasing or decreasing certain parameters, such as the price, supply and demand for oil and coal, these models could predict the consequences of a given scenario for society. Obviously, the analyses required considerable data, and Statistics Denmark and the electricity utilities soon became close collaboration partners.

The group's areas of responsibility were tailored to the Government's energy policy, and in the late 1970s were thus dealing with energy savings, conversion to new fuel types and combined heat and power production. However, for many years the main task was to assist the heating planning committee 'Varmeplanudvalget' and draw up national energy plans. In the 1980s, major changes took place in Denmark's energy supplies. The introduction of combined heat and power plants, natural gas, district heating and wind power throughout much of Denmark made the predictions about the energy sector's development and its interplay with society even more complicated, and meant that the analysis models which the systems analysis group had developed needed to be improved. At the same time, the environmental and security requirements were raised, as a consequence of which it became relevant to gather the groups at Risø working with the two issues in a single department. Risø's management therefore decided to combine the Energy Systems Group and the Risks Analysis Group on 1 January 1985. The new unit was called the Systems Analysis Department, and Hans Larsen was appointed Head of Department. Setting up the new department also followed from the fact that the final nail in the coffin of nuclear power had just been hammered in by politicians.

"Originally, Risø was, as is well known, established to explore the possibilities offered by nuclear power, until that was shelved in 1985 when the Danish Parliament decided to drop it. Setting up the Systems Analysis Department and the Wind Energy Department was a direct result of that decision," explains Hans Larsen.

FROM SECURITY OF SUPPLY TO SUSTAINABILITY

A couple of years later in 1987, the UN's Brundtland Report represented a turning point for the work of the Energy Systems Group. The report foresaw that supplies of fossil fuels would run out, and that the climate could possibly pose the biggest challenge to energy developments. With a single stroke, the climate was introduced on the political agenda not only in Denmark, but worldwide. It became a leading issue for the then Minister of Energy, Jens Bilgrav-Nielsen, a member of Poul Schlüter's Conservative-Liberal Government, who in 1990 invited the Systems Analysis Department to assist the ministry in preparing an energy plan which was bigger and more radical than any that preceded it.

"Up until 1990, focus was primarily on security of supply, but now the climate and sustainability


became the common themes for everything that we did. It was the first time that sustainability had been central to energy planning, and it has been a key element ever since," explains Poul Erik Morthorst, who was in charge of Risø's involvement in the work with the action plan for sustainable development, Energy 2000. The group worked with the project for almost eighteen months, and in collaboration with the ministry set up a number of scenarios for developments up until 2025. These scenarios have subsequently formed the basis for further work within the area. In Energy 2000, the experts concluded that a revolutionary reorganisation of the energy system was required. Among other things, far more renewable energy needed to be introduced, and large energy savings were necessary.

"There was broad political support for following the guidelines in the plan. The Danish Parliament therefore introduced the specific targets which the plan recommended," explains Poul Erik Morthorst, and continues: "This was pre-Kyoto, but it was our first step in that direction. Denmark was actually one of the first countries in Europe to address climate issues in its energy policies.

RISØ IN FRONT

The fact that Denmark was so serious about the climate concerns at a very early stage has given Risø a leading position in the development of new renewable energy technologies, and this has benefited the Systems Analysis Department in its collaboration and competition with foreign institutions. "Compared to similar groups abroad, we are obviously working with the same issues. However, with Denmark having done so well in terms of renewable energy, especially wind power, people tend to call

Risø if they want to know how to integrate wind power within large energy systems," says Poul Erik Morthorst. Theory is one thing – another is hard facts and data, and Risø has them. As a result of Denmark's now long-standing involvement with wind power, considerable experience and many data have been gathered describing how wind power functions in tandem with the other energy systems.

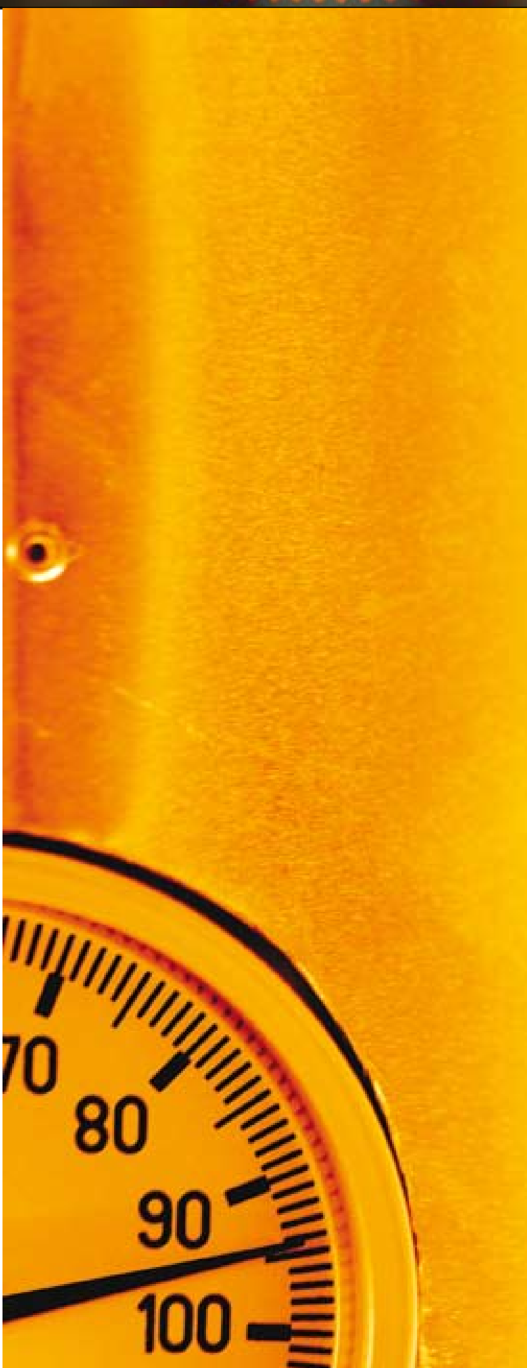
This knowledge is used in the energy systems analysis models combined with ready access to all the technological know-how within renewable energy which Risø possesses. In this way, the Systems Analysis Department has managed to develop powerful analysis models. The leading position within renewable energy has also made it easier for us to find money for research in Denmark as well as abroad, and much of the research takes place in close collaboration with foreign partners.

With the plan which the EU's Council of Ministers adopted in March 2007 aimed at reducing the impacts of climate change, knowledge about how energy systems function and how they can be adapted is needed more than ever before. The share of renewable energy must be increased, the security of supply must be improved, and our dependence on imported fossil fuels must be reduced. The CO_2 curve must be bent, so that we can face a future where emissions are half their present level or even less, explains Hans Larsen.

It is no longer a question of whether we prefer sustainable energy sources and renewable energy, but rather how and how quickly we can establish a sustainable future. The big challenge therefore is to change the energy system sufficiently quickly. Fortunately, history suggests that it can happen faster and more effectively than might be expected. In Energy Plan 1981, it was predicted that Denmark would have 50,000 small wind turbines by 2005, and which would have a combined capacity of 2,500 MW. In reality, only 5,000 turbines were erected, while capacity was 700 MW more than expected i.e. 3200 MW in 2005.

"Back then, we never believed that more than 10 per cent of Denmark's total electricity consumption could be covered by wind power, but today we are up to 20 per cent," says Poul Erik Morthorst. At Risø, no one is in any doubt that the objectives can be achieved. But action needs to be taken now.
"It is now that we need all the pieces in the puzzle to fall into place to double the share of renewable energy from 15 per cent to 30 per cent over the next twelve years until 2020. To succeed, wind power must be increased to a minimum of 50 per cent of electricity consumption, and incorporating so much wind power into the electricity system is a huge challenge," explains Poul Erik Morthorst, and Hans Larsen adds:

"We must help make the solutions slightly better than they would otherwise have been, and work to ensure that new high-tech energy technologies are taken up faster than they would otherwise have been. If we can introduce 2 per cent more renewable energy into the system two years earlier, then we will have done our job," he says.

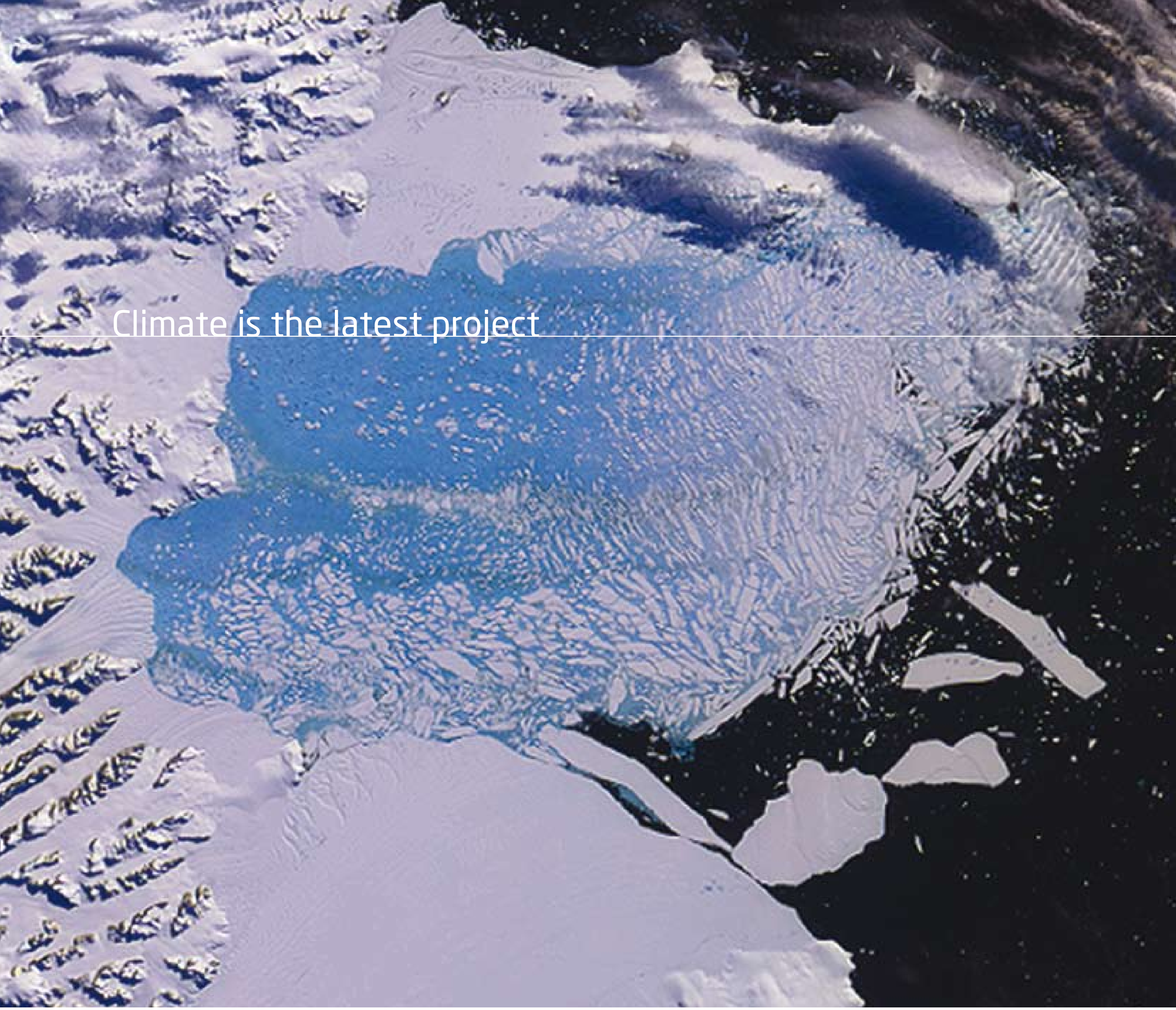


SYSLAB – from theory to practice

Lots of onshore and offshore wind turbines supply the energy in tomorrow's energy systems combined with biofuels and roof-mounted solar cells. Intelligent power consumption where the washing machine, freezer and other electrical appliances are automatically regulated according to the electricity price and weather conditions ensures flexible energy consumption. Plug-in cars with batteries and CHP plants with fuel cells in buildings can plan when to 'fill up the tank' for the following week's use. Petrol and oil are in this way replaced by energy stores which are replenished when the wind blows. In the energy system of the future, almost 100 per cent of the energy will in this way come from renewable energy, and energy production will be distributed across many units. This places significantly greater demands on controlling the energy systems compared with the conventional electricity system where relatively few coal-fired power stations share the largest responsibility for supplying electricity.

Risø has welcomed the challenge and developed SYSLAB, which is a real system in a scaled-down format where several geographically dispersed production units are connected. It is one thing to theoretically simulate energy systems in computer models – it is another to actually do it in practice. It is rare that real-life situations can be accurately described using simple models – precise parameters for these models can only be obtained once operations have commenced.

Each of the SYSLAB units is controlled by its own 'intelligent' computer which can relate to situations in the grid and react to changes in power consumption or production. The power is produced by two wind turbines, a solar cell panel, and a diesel generator, while a container-sized vanadium battery functions as electricity storage. The scientists' office building with lighting, electric radiators and coffee machines as well as a plug-in car represent the consumer. The system can be connected to the Zealand grid, which can serve as additional consumers or generators.



Climate is the latest project

THE SUN SHINES AND THE BIRDS are singing, and even though the calendar has only just switched from winter to spring, the wind is no longer bitterly cold. There is so much spring in the air that you might be led to believe that it was not 2008 but already the second half of the 21st century, and that you were really beginning to feel the effects of global warming. And in one way we actually are. At least at the top of Brandbjerg, a windswept and for many years untouched grass-clad hill in a military training zone just outside the town of Jægerspris in northern Zealand. Here, Danish scientists led by Head of Programme Claus Beier from the Biosystems Department at Risø have constructed an ingenious time machine which can whiz forwards in time to 2075.

The Larsen B ice cap on 7 March 2002 following its collapse. In the space of just over a month, a 3,250-square-kilometre ice sheet disintegrated and started to disperse. Prior to the collapse, it was about 220 metres thick. The collapse of Larsen B was for several years seen as one of the most obvious signs that global warming is affecting the polar regions. Now there are many more.

The UN's Brundtland Report from 1987 put the climate on the political agenda. Risø's knowledge about energy systems was utilised for more sustainable energy planning. The location at Risø of the UNEP's centre for energy planning in the developing countries and its contribution to the UN's climate panel (IPCC) has given Risø a key role on international energy issues.

The facility is attracting the attention of climate experts from all over the world, and it is just one of many examples that demonstrate that the former test laboratory for nuclear power at Roskilde Fjord is today regarded by many as one big centre for climate research. And one which is highly acknowledged internationally.

The time machine in Jægerspris – the so-called CLIMAITE project – simulates the effects of climate changes on vegetation. It consists of small study plots covered in heather, grass and herbs over which the greenhouse gas CO_2 is pumped. In this way, the concentration of CO_2 in the air around the plants is increased to the level which the UN's climate panel expects in 2075. The expected temperature increases are simulated by drawing a screen over the plants at night to retain the heat. This raises the average temperature by 2 degrees. Other screens ensure that the plants are exposed to the long periods of drought which are expected to be a common feature of summers in Denmark by the end of the 21st century.

And this is what has attracted international attention. CLIMAITE is unique in that, thanks to a large grant from the Villum Kann Rasmussen Foundation, it incorporates all three key factors: CO_2, water and temperature. Foreign studies have shown that it is not possible to simply combine the effects observed in studies of each of the three factors. For example, an American study concluded that plants grew 10 per cent more than normal at elevated temperatures, and 10 per cent more than normal with elevated CO_2. On the other hand, they grew 10 per cent less when both temperature and CO_2 were elevated.

"It shows that in biological research – and in climate research in general – two plus two does not always make four," says Claus Beier, who is Centre Leader on CLIMAITE. But what does two plus two make on the top of Brandbjerg near Jægerspris? We will return to this once we have taken a trip the other way in the time machine: Back to when Risø's climate work began.

Computer-generated images of the shrinking ice sheet at the North Pole in 1979 (top) and 2003 (centre). The images are based on satellite measurements. The bottom picture shows a tropical cyclone from space. It is believed that these extremely fierce storms will increase in both number and intensity in a warmer climate.

FOCUS ON CLIMATE

When, in 1987, the UN's Brundtland Report on sustainable development put the climate issue on the international political agenda, Risø was already moving away from its original focus on nuclear power. Following the Danish Parliament's final No to nuclear power in 1985, Risø became a far broader energy research centre. This meant that the methods for reliability and risks analyses which had originally been developed for assessing the conditions for space travel and nuclear power plants were to an increasing extent used to achieve greater operating reliability in industrial plants.

The extensive reorganisation of the energy systems in the 1980s and the increased focus on environmental and security requirements had by 1985 led to the establishment of the Systems Analysis Department, with Hans Larsen as head. The department was a rather atypical structure at Risø with a highly multidisciplinary composition of physicists, engineers, economists and even humanists who often had different approaches and views on subjects. However, the very discussions which were necessary to disentangle the threads have, according to employees, been one of the department's strengths – without them the links between the various fields which are necessary to produce reliable analyses would never have been identified.

Basically, the department had two main tasks: To carry out analyses that projected future developments, and to calculate the consequences for the economy and other factors related to the choice of energy source. A typical example from that time was studying the interplay between a wind turbine's technical reliability and its economic potential on the energy market. The Brundtland Report and the subsequent political repercussions in Denmark meant that climate change was also included in the Systems Analysis Department's remit. The Conservative-Liberal Government's Energy Plan 2000 from 1990, which at the time was considered very ambitious and which Risø played a key role in drawing up, stated that energy consumption in the West should now be drastically reduced to reduce the global environmental problems.

Energy Plan 2000 emphasised coherent solutions which took account of both resource consumption and all aspects of the environment. Consequently, there was even greater focus than before on environmental planning and economic analyses of the environmental consequences. This resulted in a greater need for the department's analyses. The same year, in 1990, the Ministry of Foreign Affairs of Denmark and Risø established, together with the UN's environment programme UNEP, a new centre at Risø: UNEP Collaborating Centre for Energy and Environment (UCC) – today the UNEP Risø Centre – with the objective of strengthening the integration of environmental concerns in energy planning in developing countries. The purpose was – and is – to promote the application of energy sources that can help to limit Man's environmental impact, especially the greenhouse effect.



What is global warming?

- The Earth has become approx. 0.7 degrees warmer in the past 100 years. This is such a dramatic and rapid temperature increase that the several thousands of experts in the UN's climate panel, IPCC, state that it is largely due to man-made influences, and that the temperature will continue to rise in future.
- The culprit is the greenhouse gases: Methane, CFC, ozone and, in particular, CO_2, which is the main waste product from the combustion of fossil fuels such as coal, oil and natural gas. Greenhouse gases are found naturally in the atmosphere where they prevent the loss of solar heat into space. However, man-made emissions have increased the amount of CO_2 to levels that are far in excess of those seen over the past min. 600,000 years. This means that more solar heat is retained, and the climate becomes warmer.
- How much warmer the Earth will become depends, among other things, on whether and when the world's leaders can agree on bending the CO_2 curve. In its latest report from 2007, the IPCC calculates that by 2100 the Earth will be between 1.8 and 4.0 degrees Celsius warmer on average than it is today, if emissions are not reduced.
- This means less ice, especially around the North Pole, and probably more flooding, especially in poorer parts of the world. More people are expected to have problems obtaining clean drinking water.
- The industrialised nations, with the exception of the USA, agreed in the Kyoto Protocol to reduce their emissions by 5 per cent in the 2008-2012 period compared to emissions in 1990. The hope is that a far more ambitious target will be set at the climate summit in Copenhagen in December 2009, and also that the USA and large developing countries such as China, India and Brazil will accept formal commitments.
- The IPCC, with, among others, Risø's Kirsten Halsnæs, assesses that the climate changes can be kept below 3 degrees by investing just over 1 per cent of world GDP annually. Their analyses suggest that it will cost far more if no action is taken, and that the longer we wait, the more expensive it will be.

Sources: IPCC etc.

WHAT CLIMATE PROBLEM?

Head of the UNEP Risø Centre, John Christensen, and other scientists at Risø were almost from the outset involved with the UN's climate panel which was also established in 1990. However, despite an intense international discussion throughout the 1990s, climate change did not play a prominent role in how Risø perceived itself. In Risø's 560-page 40th anniversary book from 1998 – a few months after the Kyoto Protocol was signed – the climate issue is only sporadically mentioned in a number of subsections.

"Historically, Risø's approach has not involved working with the climate, and this influenced attitudes for a long time. Many people didn't really know what the Kyoto Protocol was, not even out here. There was hardly anyone who would not like to discuss climate issues, but it was very rarely a focus area," recalls Hans Larsen. According to him, however, this was more of a reflection of general political and public awareness about the problems than any actual prioritisation.

The change of government in November 2001 emphasised this. The new government listened to the sceptics who questioned whether the climate changes were actually as big a problem as the UN's climate panel believed, and a number of initiatives regarding the climate and renewable energy, by then core research areas at Risø, were put on hold. However, Risø's activities in this area did not ungergo any significant setback as a result – neither in the UNEP centre nor at the Systems Analysis Department or the large parts of Risø that were contributing to climate research by developing new energy technologies – if anything, the opposite happened. During this period, the Systems Analysis Department focused increasingly on international activities and was for example elected as European representative on the board of the UN's climate panel – represented first by John Christensen and from 2003 by Hans Larsen.

Moreover, Risø scientists such as Kirsten Halsnæs, Jørgen Fenhann and Amit Garg became involved as key scientific authors on the UN panel's fourth report, which was prepared in the 2001-2007 period.

"You could say that we just continued working on what has always been Risø's main task: Developing new energy technologies to ensure security of supply by replacing oil, while it might also promote commercial interests," says Hans Larsen.

During this period, the UNEP Risø Centre worked extensively on developing the Kyoto Protocol's so-called Clean Development Mechanism, whereby industrialised countries purchase the right to emit more CO_2 by investing in projects that reduce emissions in developing countries. The idea is that there are more easy options for clean development in the poor countries, and it therefore makes sense in the overall accounts to make the reductions where you get most value for money, among other things because we in the West have already picked the low-hanging fruits in our countries: the relatively easy energy savings. In poorer parts of the world, it is still possible to get a lot of relatively cheap environmental improvements for your money by investing in flue gas filters, treatment plants and other initiatives which have become pretty well standard in the West.

A WIND OF CHANGE

Even though the UNEP Risø Centre and the other climate scientists continued to work during the 'climate-sceptical period', it was nevertheless a relief for the scientists when the political winds changed, and from 2004 and onwards the Liberal-Conservative Government became increasingly green and climate-progressive. Risø was given new work; for example, the UNEP Risø Centre helped to shape Danida's new strategy for development and climate, where climate considerations were incorporated into the planning of development projects. The centre, which started modestly with just four employees, is now staffed by a 30-strong team and has gradually increased its project activities and so acquired greater possibilities for introducing environmentally and climate-friendly energy sources in developing countries – which, of course, will be the hardest hit by climate change but which have the least capacity to mitigate the effects.

It all culminated – provisionally – in 2007 with the focus on climate at the G8 meeting and at the special climate meeting organised by the UN Secretary General, and with an unusually broad recognition of the reports from the UN climate panel, and not least thanks to a Nobel Peace Prize, with Risø also sharing some of the credit along with all the other authors. And on the domestic political scene, a new energy plan was adopted.

"In the space of just a few of years, the political climate has been almost turned upside down. Even though there are occasionally contrary reports in the media, global warming has, generally speaking, been so universally accepted that people refrain from talking about it improperly, as if it were something that might upset one's old grandmother. You just don't do it," says Hans Larsen.

"On the other hand, there is nothing to suggest that the problem has to be solved through lowering standards of living and only eating hot food twice a week," interjects John Christensen – and Hans Larsen nods in agreement: "Solving the climate problem must go hand in hand with continued development and growth. This is why Risø is and, by all accounts, will continue to be a key player. We have a lot of experience in this field: Developing cleaner energy technologies which can pay their way," he points out. Among the cleaner technologies which can help to solve the climate problem, he mentions in particular hydrogen and super batteries, which can hold much more power per kilo, as well as being faster to recharge.

RISØ PRODUCES KNOWLEDGE ABOUT NATURE'S REACTION

Back at Brandbjerg – the time machine at Jægerspris – Risø scientists are in the process of drawing up qualified predictions about the future. The most important question in the experiment is whether the ecosystems will react as a buffer in relation to the climate changes or whether they will in fact reinforce them: Will the plants be able to withstand drought and heat and utilise the extra CO_2, so they will grow more and absorb more CO_2 from the air? Or will the higher temperatures increase the rate of decay of dead plant material so much so that more stored carbon will be released from the soil and the greenhouse effect thereby accelerate?

The first results suggest that plants are capable of tolerating periods of drought and maintain relatively good growth when the level of CO_2 in the air increases, and counteract any acceleration in the greenhouse effect. However, it is too early to say how all three factors will interact. There are also other challenges for nature. Some plants are better at adapting than others, and these will find it easier to survive and spread, and new species will appear, while others will be overcome and become extinct. The Brandbjerg experiment, which runs provisionally until 2013, helps to illustrate that we cannot just pollute without consequences for the ecosystems. And the three climate scientists Claus Beier, Hans Larsen and John Christensen all feel a shared sense of responsibility for supplying the knowledge which is necessary for the political and technological solutions that must ensure that mankind overcomes the challenges. It is here that the scientists and research centres such as Risø are able to make a difference. After all, there is no doubt that the Earth as a planet will probably survive:

"But with global warming, we are putting many animal and plant species in danger. And at the end of the day, also ourselves," adds John Christensen.

UNEP Risø Centre helped Indian children to improve their school marks

It rarely helps to support the sale of products that will never be able to be attractive on market terms. But what if the market just needs a gentle push in order to become effective? This was what the UNEP Risø Centre's thought when, in 2003, it developed the so-called Indian Solar Loan Programme together with two of the largest commercial banks in India, Canara Bank and Syndicate Bank. In May 2007, the programme was awarded an Energy Globe Award, the Oscar-equivalent for energy.

The programme results led to it becoming easier in the two Indian states to borrow money for solar lighting installations. The loans could only be granted for certified installations to ensure quality products. Moreover, the loan procedures were simplified and for the initial period interest payments were subsidised. The project was a success, because there is a considerable lack of stable energy and electricity supplies in the rural parts of India. The two banks have made money, and there is now such a stable investment climate for small solar cell installations that the other banks in the areas have joined in, operating on ordinary market conditions. The 17,000 solar cell installations which have so far been sold have improved the lives of 100,000 people: Each solar installation makes it possible to run a handful of 20 or 40-watt bulbs and perhaps a radio, TV or fan for a couple of hours every evening.

The extra hours of electricity have, among other things, meant that schoolchildren have been doing better at school as they have been able to do their homework after sunset. At the same time, production from smaller home factories and cottage industries has increased significantly.

The UNEP project has also spread to other states in the country, and similar projects in China, Indonesia, Mexico and Algeria are in the pipeline.

PHOTOGRAPHERS

Front page: Thomas Arnbo
p. 4: Thomas Arnbo/Risø DTU
p. 5: Thomas Arnbo/Risø DTU
p. 7: Marianne Ryde/Risø DTU
p. 8: Risø DTU, Risø DTU, Risø DTU, Risø DTU
p. 9: Risø DTU
p. 10: Risø DTU
p. 11: Risø DTU
p. 13: Boye Koch/Risø DTU, Risø DTU
p. 14: Risø DTU
p. 15: Boye Koch/Risø DTU
p. 16: Boye Koch/Risø DTU
p. 17: Risø DTU
p. 18: Boye Koch/Risø DTU
p. 21: Risø DTU, Boye Koch/Flemming Rasmussen/Risø DTU
p. 22: Lars Bahl/Risø DTU
p. 23: DTU's Course Catalogue 2008
p. 25: Risø DTU, Boye Koch/Risø DTU
p. 26: Lars Bahl/Risø DTU
p. 27: Lars Bahl/Risø DTU
p. 28: Lars Thornblad/Risø DTU
p. 29: DTU's Course Catalogue 2008, Lars Thornblad/Risø DTU
p. 30: Lars Bahl/Risø DTU
p. 32: Boye Koch/Risø DTU
p. 33: Lars Bahl/Risø DTU
p. 35: Lars Bahl/Risø DTU
p. 36: Lars Bahl/Risø DTU
p. 37: Lars Bahl/Risø DTU
p. 38: Lars Bahl/Risø DTU
p. 40: Lars Thornblad/Risø DTU
p. 41: Morten Corneliussen, Exit Fotostudiet/Risø DTU, Lars Bahl/Risø DTU
p. 43: Lars Bahl/Risø DTU, Lars Bahl/Risø DTU
p. 44: Lars Bahl/Risø DTU, Lars Bahl/Risø DTU
p. 45: Lars Bahl/Risø DTU
p. 46: Risø DTU
p. 47: Lars Bahl/Risø DTU, Lars Bahl/Risø DTU
p. 48: EFDA-JET
p. 49: Risø DTU
p. 51: Lars Thornblad/Risø DTU
p. 53: EFDA-JET; Göran Scharmer, Kai Langhans, ISP/ Royal Swedish Academy of Sciences
p. 54: Lars Bahl/Risø DTU
p. 55: Lars Bahl/Risø DTU
p. 56: Lars Thornblad/Risø DTU, Lars Thornblad/Risø DTU
p. 59: Gitte Sofie Hansen/Risø DTU
p. 60: Risø DTU
p. 61: Risø DTU
p. 63: Lars Bahl/Risø DTU, DTU's Course Catalogue 2008
p. 64: Boye Koch/Risø DTU, Lars Bahl/Risø DTU
p. 67: Boye Koch/Risø DTU; Boye Koch/Risø DTU
p. 68: Lars Bahl/Risø DTU, Lars Thornblad/Risø DTU
p. 69: Lars Bahl/Risø DTU
p. 70: Risø DTU, Lars Bahl/Risø DTU, Lars Bahl/Risø DTU
p. 72: Boye Koch/Risø DTU
p. 73: Risø DTU
p. 75: Risø DTU, DTU's Course Catalogue 2008
p. 76: Lars Thornblad/Risø DTU, Lars Thornblad/Risø DTU
p. 79: Danish Decommissioning, Danish Decommissioning, Danish Decommissioning
p. 80: Lars Thornblad/Risø DTU
p. 81: Lars Bahl/Risø DTU
p. 83: Lars Thornblad/Risø DTU, Lars Bahl/Risø DTU
p. 85: Lars Bahl/Risø DTU, Lars Thornblad/Risø DTU
p. 87: Lars Bahl/Risø DTU, Lars Bahl/Risø DTU
p. 88: NASA/GSFC/LaRC/JPL, MISR Team
p. 89: Lars Thornblad/Risø DTU
p. 91: NASA, NASA, NASA
p. 92: Lars Thornblad/Risø DTU, Lars Thornblad/Risø DTU
p. 95: DTU's Course Catalogue 2008

Risø DTU
National Laboratory
for Sustainable Energy

ISBN: 978-87-550-3671-0